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FINAL REPORT

on

CRITICAL MATERIALS NEEDS

Sponsored by

DEFENSE ADVANCED RESEARCH PROJECTS AGENCY
Technology Assessments Office

August 11, 1975

by

Curtis M. Jackson, James O. Frankosky,
and Joseph G. Dunleavy

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FOREWORD

The research and analysis reflected in this report were performed by Battelle's Columbus Laboratories. The project is supported by the Defense Advanced Research Projects Agency (ARPA) of the Department of Defense (DoD) and is monitored by the U. S. Army Missile Command, Redstone Arsenal, Alabama, under Contract No. DAAH01-75-C-0338. Mr. Rudolph A. Black, Director, ARPA Technology Assessments Office, (until his departure in June 1975) and Dr. Stanley Ruby, ARPA Materials Science Office, were the Technical Monitors of this effort.

DISCLAIMER

The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the Defense Advanced Research Projects Agency or the U. S. Government.

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INTRODUCTION

During this century the rapid increase of technological advances and their incorporation into weapon systems and materiel have often created unforeseen demands for raw materials and consequent shortages and economic rivalries among friendly as well as hostile nations. Such situations are often further aggravated and intensified by the onset of major military conflicts. The shortage of rubber and copper in World War II, the stockpiling of many metals during the Korean War, and the search for uranium ore during the 1950's are well-known historical examples. Within the past few years the oil-producing countries have used embargo and price increase measures as a means of getting more funds from the developed nations of the world. This has encouraged other countries possessing vital raw materials to consider actions such as when Jamaica increased its export tax on bauxite 700 percent in 1974. (1)*

In such circumstances, the United States has many times found it necessary to categorize certain raw materials as essential or critical. To ensure adequate supplies of critical materials the Department of Defense (DoD) has then taken action to initiate material conservation measures (including design changes), materials substitution programs, and/or raw materials stockpiling. It would be most helpful to the DoD if it could better anticipate the need for such measures through prior assessment and analysis of technological trends which impact on the U.S. requirements for materials or associated manufacturing processes which could be classed as critical. This research project addressed those needs by making an assessment of emerging industrial technologies in the United States, with particular emphasis on six technologies which were selected for extensive analysis.

TECHNICAL OBJECTIVES

The objectives of this research effort were to:

- Select, through preliminary analysis of fifteen major U.S. industries, a number of U.S. emerging technologies for detailed assessment.

- Analyze the selected U.S. technologies for possible criticalities to the U.S. in material availabilities and production capacities by 1990.

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* For specific identification of information sources, refer to References on page 109.

- Identify any potential procurement and development problem areas which could possibly evolve for the DoD in the light of the anticipated criticalities.

TECHNICAL APPROACH

The initial phase of the research program was a screening study devoted to the identification of emerging technologies* in 15 U.S. industries through interviews with Battelle specialists having knowledge and expertise in those industries. Some 57 emerging technologies were identified as possible candidates for further study. A list of the 15 industries, the related industrial technologies, and the cognizant Battelle specialists is given in Appendix A. After further screening, six of the technologies were recommended to and approved by the Defense Advanced Research Projects Agency (ARPA) for continued research and in-depth analysis.

The remaining research then focused on the six selected technologies. The technical description of each emerging technology and its requirements for critical materials and for major materials-production capacity were obtained from Battelle specialists and through personal contacts with appropriate industry and government personnel. The personal contacts are listed in Appendix B. The projections of supply/demand and costs of the materials were based on data from Battelle and industry sources, from selected government and industrial reports, and from oral presentations at the DoD Material Shortages Workshop (2) and the National Conference on Materials Availability/Utilization.(3) General projections of the future availability of major capacity for the production of materials were also obtained from industry sources, to the extent that such information was readily available.

The research concluded with the identification of procurement and development problem areas which may possibly evolve for the DoD. These conclusions were based on analysis of the information received from the various in-house, industrial and government sources concerning each of the six technology areas.

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* For the purpose of this research, emerging technologies are defined as those which are expected to become increasingly accepted by industry in the next 15 years, to the extent that their market penetration is anticipated to be significant by the year 1990. However, ARPA requested that this research devote minimum attention to the Energy and Food and Agriculture industries inasmuch as they are being otherwise studied.

OVERALL SUMMARY AND CONCLUSIONS

An overall summary of the results of the research is given in Table I, which outlines the principal factors and results associated with the six industrial technologies that were studied in depth.

The conclusions that were reached in the conduct of this research are summarized as follows:

Of the six technologies that were studied in depth, two face potential problems in having an adequate supply of raw materials available to support future production. These materials are platinum-group metals for fuel cells and helium, niobium, copper, nickel and chromium for superconductors. However, in the latter technology, significant needs for the necessary raw materials should not obtain until the post-1990 time frame.

In five of the technology areas, it appears to be possible for the anticipated domestic demand to exceed presently available estimates of future U.S. production capacities, and thereby adversely impact on availability of associated materials tailored to meet specific DoD needs. These include electroslag remelted (ESR) steels, graphite and boron fibers for fiber-reinforced composites, fiber optics for lasers used in communications, silicon nitride for high-temperature gas turbine engines, and superconducting alloy (Nb_3Sn, NbTi) wire. Again, for superconductors, significant demand would be subsequent to 1990.

The anticipated DoD needs for materials or products which evolve from these six technologies are small in comparison with the total estimated demand. The DoD may therefore experience difficulty in competing on the market for its procurements needs - unless private sector or government actions are able to motivate and cause greater production capacities than are currently evolving.

DoD development problems, most of which are currently being addressed by the respective Service(s), are noted in:

- Identifying viable alternatives, to the present fuel processor for mobile fuel cell power units.

- Adapting design approach and developing economical fiber and composite fabrication methods for fiber-reinforced composites in weapons systems.
- Adapting and interfacing laser communications utilizing fiber optics into weapons systems and command and control facilities.
- Fabricating fiber optic cable with requisite ruggedness, strength and other necessary characteristics.
- Adapting superconducting technology to naval ship propulsion, aircraft lightweight generators, and high-power ground weaponry, and
- Adapting design approach and economical ceramic fabrication methods to meet specific DoD material characteristics.

DETAILED PROGRAM RESULTS

Initial Screening Study

During this phase of the research, 57 emerging technologies were identified in the 15 U.S. industries. Fifty-one of the 57 were determined not to meet the criteria for further study as fully as the six selected for in-depth study. The 51, as well as their individual criticality considerations and basis for non-selection for further study, are tabulated in Appendix C. The criteria and factors that were considered in making the value judgments to select the six technologies are listed on the first page of the same appendix. It was recognized in the approach being employed, which was to do only a preliminary screening analysis of the 57 being considered with few industrial contacts, that some of the emerging technologies not selected could possibly have been found qualified for subsequent analysis, if more extensive research had been undertaken in the initial phase.

The detailed results of the six technologies further studied are described below to include the name(s) of the key Battelle researcher(s) involved in each technology.

TABLE 1. SUMMARY - SIX SELECTED U.S. EMERG

Emerging U.S. Technology	Description	Criticality Basis	Projected[a] Market	
Electroslag Remelting (ESR) (of steel)	Melting of electrodes in a high temperature slag to produce a refined metal alloy of high purity and uniformity, with many other desirable qualities.	Inadequate ESR production capacity in U.S.	~200,000 tons (1975)[b] Free World ~1,500,000 tons (1990) - Free World ~70,000 tons (1975)-U.S. ~700,000 tons (1990)- U.S.	Gun pla air ing mis
Fiber-Reinforced Composites	Reinforcing fiber in a resin or metal matrix to achieve desirable material properties such as extremely high tensile strength and modulus-to-weight ratios.	Possibly inadequate production capacity in U.S. for graphite fibers and boron fibers.	• Graphite fibers ~140,000 lb used (1974) - U.S. ~10,000,000 lb (1981) - U.S. ~100,000,000 lb (1990) - U.S. • Boron fibers ~20,000 lb (1975)-U.S. ~200,000 lb (1990)- U.S. • Aramid (Kevlar) fibers ~5,000,000 lb[c] (1975) - U.S. production capacity ~50,000,000 lb[c] (1980) - projected U.S. production capacity	• G • B • B • A

(a) Figures rounded. See detailed text for more precise data.
(b) ~1,000,000 tons (1975) - USSR.
(c) Figures include all uses of Kevlar, not only composites.

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ED U.S. EMERGING INDUSTRIAL TECHNOLOGIES

d[a]	DOD Projected Needs	DOD Potential Problems	Remarks
1975)[b] (1990) - 975)-U.S. (1990)-	Gun tubes, armor plate, ship plate, vehicle structures, aircraft structures and landing gears, helicopter rotors, missile casings.	Possible lack of U.S. production capacity to insure U.S. needs are met. Some military development program requirements currently being delayed because of shortages in ESR materials.	Only one U. S. plant for plate-ingot production exists at present. Heavy foreign initiative and competition in ESR field causes concern, particularly since with its present rate of growth U. S. capacity would not be able to meet the estimated domestic demand.
s sed b 975)-U.S. (1990)-) fibers c) . pro- city (c) jected ion	• Graphite/epoxy: B-1 and other aircraft structures and surfaces, helicopter rotor blades, transmission shafts. • Boron/epoxy: F-14, F-15 tail surfaces, C-5A leading edge slot, F-4 rudder, CH-54B tail-cone. • Boron/aluminum: Space Shuttle fuselage truss structure; also being evaluated are various structures such as B-1 longeron & rib, wing box for S-3A, A-7 landing gear struts. • Aramid fiber composites: aircraft floor panels, fairings, control surfaces, radomes, doors, panels, cargo liners, helicopter parts; also being considered for such as bullet-proof vests, helmets, armored vehicles.	• Development of economical automated fabrication methods to avoid hand operations • Development of boron fibers with graphite fiber as a substrate. • Development of innovative approaches at conceptual design phase of systems development. • Accurate assessment of cost/performance trades in the increasingly severe "design-to-cost" environment.	Biggest problems for DoD seem to center on adapting design approaches and economical fiber and composite-manufacturing methods to embrace this new technology which shows great promise to meet advanced weapon systems needs.

TABLE 1

2

TABLE 1 (Continued)

Emerging U.S. Technology	Description	Criticality Basis	Projected[a] Market	
Fuel Cells	Electrochemical device for converting hydrogen or hydrogen compounds from chemical fuels directly into electrical energy (at higher efficiency than most other present energy conversion means).	Reliance on availability from foreign sources of platinum group metals for use as catalyst materials in fuel cells.	Fuel cells (or water batteries) ~20,000 MW installed (1990) - U.S., requiring: ~10,000,000 troy oz.[b] of platinum group metals	• 91, for beg Pla exc tio • Al und
Lasers for Communications and Materials Processing	Electromagnetic radiation from an active (amplifying) medium in a resonant cavity. Distinctive by its coherence and small beam divergence, so as to permit propogation of laser energy in a highly concentrated beam. Uses are many and varied, the one of interest herein being transmission through fiber-optic wave guides in communications.	Possibly inadequate fiber optic production capacity in U.S.	Fiber Optics ~120 lb. (1000 miles) (1975) - U.S. production capacity ~700,000 lb. (6,000,000 miles) (1990) - U.S.	• Ba co • Un sy sh • Ai

(a) Figures rounded. See detailed text for more precise data.
(b) Assumes technology has improved from current 20 g/kW to 13.5 g/kW of platinum required in fuel cells.

2

1 (Continued)

)	DOD Projected Needs	DOD Potential Problems	Remarks
ater talled ., oy oz.[b] group	• 91,000 mobile power units for ground tactical use beginning in 1981. Platinum needs should not exceed 3% of U.S. production in any year. • Also, space and possible underwater applications.	• Possible difficulty in insuring availability of platinum group metals to DOD if competitive U.S. market needs for the materials evolve, or if these materials from foreign sources become unavailable. • Possible R&D alternatives for a fuel processor.	No problem in platinum availability at present, although platinum is currently critical (on the U.S. stockpiling list). Present Bureau of Mines forecasts indicate it is unlikely that domestic production will ever satisfy much of U.S. needs.
miles) . pro- city iles) .	• Base and command post communications. • Undersea surveillance systems and on-board ship communications. • Aircraft avionics systems.	• Possible shortage of U.S. production capacity of fiber optics to meet domestic U.S. needs and the consequent market competition for the material. • Possible fiber optic systems development and interface problems. • Development of fiber optic cables with the requisite ruggedness, strength and other characteristics.	No criticality presently envisaged in laser materials for materials processing technology. (After further analysis, neodymium - YAG availability no longer envisaged to be the possible problem identified in the interim technical report).

TABLE 1
(Continued)

2

TABLE 1 (Continued)

Emerging U.S. Technology	Description	Criticality Basis	Projected[a] Market	D
Superconductors for Power Applications	True thermodynamic state which is characterized by infinite electrical conductivity and perfect diamagnetism. Technology is leading to applications such as electrical power generation and transmission, motors, energy storage, and plasma confinement in thermonuclear fusion and magnetohydrodynamics.	• Possibly inadequate availability of helium, niobium and copper. • Possibly inadequate availability of nickel and chromium for non-magnetic structural steels. • Possibly inadequate production capacity for superconducting alloy wire.	• Helium - cumulative demand (all uses) [b] ~2.5 Gcf (1970-1974)-U.S. ~77 Gcf (1975-2000)-U.S. ~470 Gcf (2000-2050)-U.S. • Niobium - (in superconducting alloys) ~35,000 lb (1974)-U.S. >300,000 lb (1990)-U.S. [c] • Copper - (superconductor use) ~10,000,000 short tons or more (21st century) - World • Superconducting alloy wire or tape (e.g. NbTi or Nb_3Sn) ~50,000 lb. (1975)-U.S. >300,000 lb. (1990)-U.S. [c]	• Aircr gener • Naval • High • Mobil gener
High-temperature Gas-Turbine Engines for Automotive Applications.	Operating gas turbines at high temperature to gain higher combustion efficiencies and improved fuel economy. Of particular interest is the utilization of ceramics to achieve the higher temperature capability.	Possibly inadequate production capacity of ceramic (silicon nitride and possibly, silicon carbide) gas turbine engine components.	• Silicon nitride components ~Laboratory scale (1975) U.S. ~15,000,000 lb. (1990) U.S.	• Dro veh • Aux for • Co tr

(a) Figures rounded. See detailed text for more precise data.
(b) Gcf = 10^9 standard cubic feet.
(c) Estimated cumulative demand through 1990: niobium in superconducting alloys - 5,000,000 lb; superconducting alloy wire and tape - more than 5,000,000 lb.

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1 (Continued)

)	DOD Projected Needs	DOD Potential Problems	Remarks
lative es) (b) 0-1974)- -2000)- 0-2050)- super- lloys) 974)- 1990)- (c) rcon- ort tons t cen- d g alloy e.g.) 975)- (c) 1990)-	• Aircraft electric power generation. • Naval ship propulsion. • High power land weaponry. • Mobile, modular power generators.	• Possible shortage of helium, niobium copper. • Possible shortage of nickel and chromium used in non-magnetic structural steels. • Possible production lack in superconducting alloy wire or tape. • Development of superconducting motors/generators for shipboard use, lightweight refrigerators for high-power weaponry and lightweight airborne generators.	• It appears now that the greatest demand for these materials will occur subsequent to 1990 when impact of superconductor technology would be felt.
ide com- scale . lb. .	• Drones, remotely piloted vehicles, and missiles. • Auxiliary power units for aircraft. • Combat vehicles (tanks, trucks).	• Possible inadequacy of U.S. production capacity for ceramic components to meet domestic U.S. needs and the consequent market competition for the material. • Development of design criteria and economical fabrication methods for complex ceramic components of the requisite properties for DoD applications. • Solution for the metal/ceramic interface problem.	• Biggest problems for DoD seem to center on adapting design approaches and development of economical ceramic fabrication methods to meet specific DoD material characteristics.

TABLE 1
(Continued)

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Electroslag Remelting

by

Joseph G. Dunleavy

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Electroslag Remelting

by

Joseph G. Dunleavy

Technical Description of the Technology

Introduction. Metals and alloys with high levels of quality and purity have become an intrinsic part of the development and production picture. The present state of knowledge and technology in this area was to a large part acquired in the process of satisfying the demands generated by aerospace, nuclear, and military activities. These requirements involved operation of metallic materials over wide ranges of temperature, under critical loading conditions (static, impact, and vibrational), through severe thermal cycling, and in environments which included radiation, chemically aggressive media, and vacuums. These requirements necessitated not only the development of new alloys but also the achievement of exceptionally high levels of quality to insure reliability and to extend service life. Conventional melting methods even when upgraded failed, in many instances, to meet the standards required. The electroslag remelting process is one of the most promising methods available for the production of high-purity metals in tonnage quantities with the flexibility to produce product in various shapes.

History. The electroslag remelting process (ESR), currently identified as a foreign process, is an example of "reverse technology transfer". The process is a U.S. invention. R. S. Hopkins applied for patents on the process in 1935; these were granted in 1940. During World War II ESR, then known as the "Kellogg Electric Ingot Process", was used to produce high-grade tool steels and welding rod for the welding of armor plate.[4] In 1947, the first high-temperature alloy Timken 16-25-6 (Fe-16Cr-25Ni-6Mo) was successfully melted by ESR. This success was rapidly followed by the successful melting of a number of high-temperature alloys. Although the results achieved in the U.S. were excellent, the process was not really exploited. In 1959, the Hopkins patents were sold by the Kellogg company to the English firm of Firth-Sterling for the production of tool steels.

The potential production of metals in tonnage amounts by the ESR process (U.S. Hopkins process) was completely submerged in the U.S. and Western Europe by the vacuum arc remelting process and by the vacuum degassing of conventionally melted steel. The revival of interest in the ESR process, primarily in Western Europe, occurred concurrently with the appearance of Soviet publications in the 1950's.[5] The ESR process then spread from the USSR to Western Europe, the U.S., and Japan, completing the transfer cycle. In fact activity on ESR remained relatively low in the U.S. well into the late 1960's. For example, at the first International Symposium on Electroslag Remelting held at Pittsburgh, Pennsylvania, in 1967, the contribution of U.S. industry and the U.S. technical community was small.

The Soviet's entry into the ESR process was apparently a natural outgrowth of their interest and efforts in the electroslag welding field. By 1956 the Paton Institute in Kiev, USSR, had designed and built a commercial furnace for the production of 1/2-metric-ton ingots.[6] This furnace was rapidly followed by improved versions so that by 1960 10-ton ingots were being produced on a commercial basis. Larger furnaces followed, with capacities for producing 40-ton ingots in 1968 and 60-ton ingots in 1970. The estimated production of ESR ingots in the USSR for 1975 is 1,000,000 tons.[6] The largest ESR furnace now in operation is a 165-metric-ton unit at Rochling-Burbach Steel, West Germany. This furnace was built by the Leybold-Heraeus Company of Hanau, West Germany.[7]

Although the Soviets made the major contribution to the ESR process, significant work on the metallurgical and engineering aspects were made in Austria, England, Germany, and the U.S. The present concentrated research and development effort in Japan, however, may give the Japanese the technical lead in the Western world in the future.

The Process. Melting in the ESR process is accomplished by the melting of an electrode or electrodes in a bath of molten slag (flux). The molten droplets collect in a pool below the slag layer, and are solidified into an ingot as the process progresses. Solidification is accelerated by the use of water-cooled copper molds. Figure 1 is a sectional view of the process in a Soviet bifilar system utilizing a stationary mold (bifilar refers to the method of electrical circuitry used and will be subsequently discussed). The heat required for melting is obtained from the heat generated by the passing of electrical current from the electrode(s) through the electrically conductive slag. The electrical resistance of the slag is a function of its chemical composition.

The formation of metal drops during the ESR process greatly increases the metal/slag interface area and allows a significant refining of the metal to be performed by the high-temperature slag. In addition, the high thermal gradients across the molten metal/solid metal interface yield very low levels of segregation in the ingot. The product is a high-purity metal with low levels of inclusions, segregation, and porosity, and a high uniformity of mechanical properties in the length, width, and thickness dimensions.

As is evident from the preceding discussion, ESR is a remelting process for the production of high-purity metals. In the process, electrodes are first melted by some other method. The electrodes in turn are remelted. At the present time there are three other remelting processes: vacuum arc remelting (VAR), plasma arc remelting (PAR), and electron beam remelting (EBR). The VAR process is well established in the U.S. and Western Europe. PAR is still in the developmental stage. The use of EBR can only be justified in applications requiring very low levels of impurities. In general EBR has fulfilled the role of melting the refractory metals such as tungsten and tantalum.

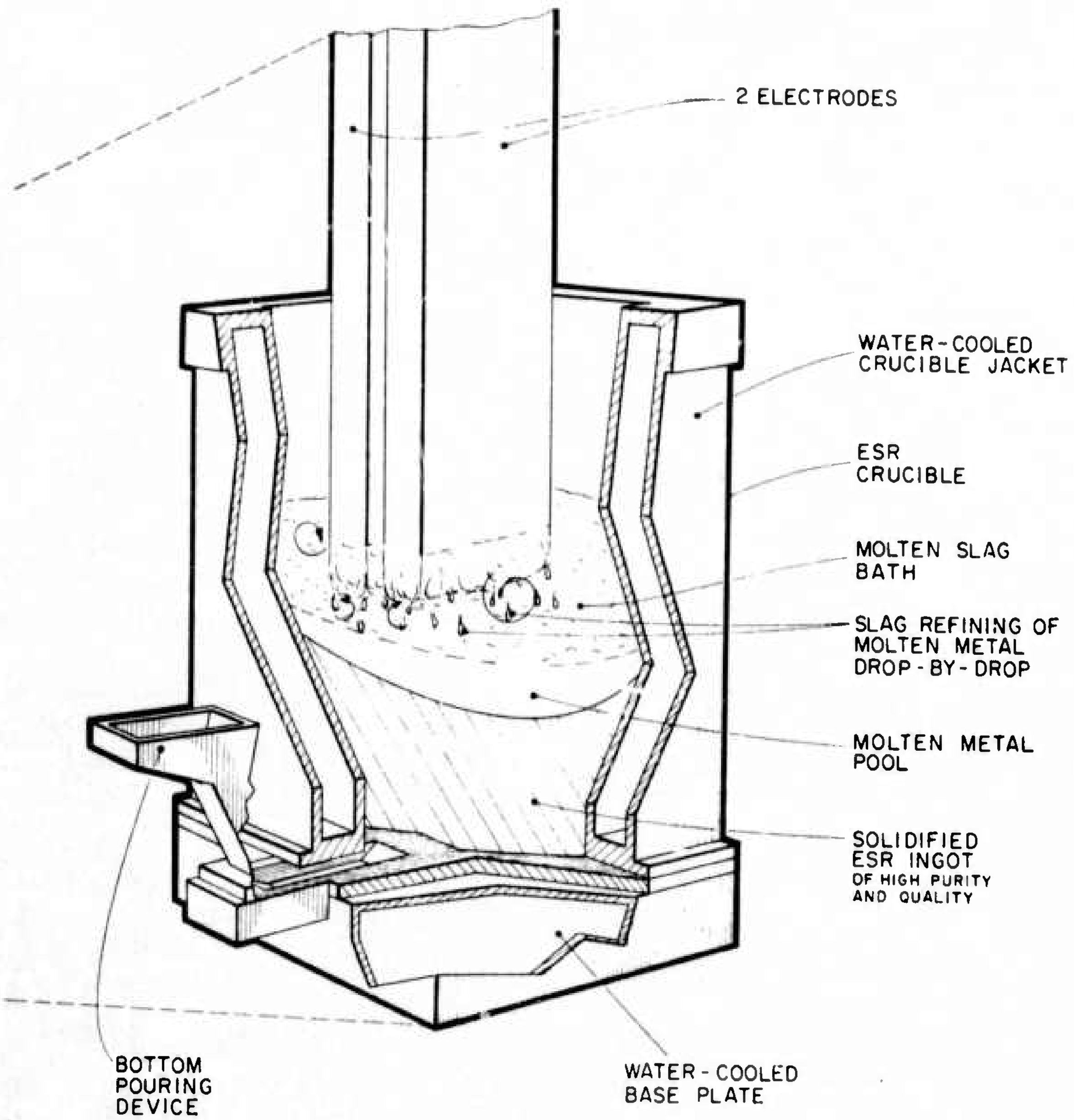

FIGURE 1. BIFILAR ESR CRUCIBLE (SECTIONAL VIEW)(6)

ESR and VAR are processes that have been in open competition over the past 10 years with ESR capacity increasing at a much higher rate than VAR. Up to the present there has been considerable controversy as to the merits of each process. In general, however, the following points are universally accepted.

ESR	VAR
(1) Greater process flexibility with respect to electrode and ingot geometry (slab ingots, hollow ingots, castings)	(1) Higher levels of purity
(2) Increased ingot yield	(2) Lower power consumption per ton melted
(3) Increased workability	(3) Ingot size limit of about 50 tons
(4) Higher power consumption per ton melted	(4) Not amenable to the production of slab or hollow ingots or shaped castings.
(5) No real limit on ingot size	
(6) Reduction of the sulfur content	
(7) Stable operation on alternating current at industrial frequencies.	

There have been few direct comparisons of the two processes involving enough metal for a statistical judgement. One of these, however, is the melting of the nickel-base alloys by the Cabot Corporation. By 1971 the Cabot Corporation had melted by ESR 41 million pounds of the Hastelloy X (Ni-Co-Cr-Mo-W-Fe) alloy. A statistical analysis of the processes showed microcleanliness to be better, microsegregation appeared to be less (although this is a subjective conclusion), and mechanical properties were more uniform for ESR melted material than for VAR. In addition to these advantages, the inherent advantages of ESR--higher ingot yield and improved workability were also realized.

Slags. One of the important ingredients in the ESR process is the slag; its chemical composition is critical. Normally, the principal components are calcium fluoride, aluminum oxide, and calcium oxide. However, various other compounds are occasionally used (i.e., magnesium oxide, barium oxide, titanium oxide, and boron oxide) depending upon the metals being melted. The slag composition selected is in all cases a compromise between factors such as the desired degree of sulfur

removal, process stability, ingot production rate, power consumption, ingot surface quality, and element loss.

A considerable amount of effort has been spent studying the metal-slag reactions, and the effect of slag composition on operating parameters and quality of the product. Efforts in this area are continuing and the results obtained will further improve the ESR process and product.

Electrical Power Modes. The ESR process has an unusually high degree of flexibility relative to the type of electrical power mode used. The process can be successfully operated on d-c with negative or positive polarity and on a variety of a-c combinations (single phase, bifilar, three phase, and four phase), Figure 2. At the present time essentially all furnaces are operated on a-c.[5,8,9,10] Frequencies are either in the range of 50-60 hertz or 2-10 hertz. In all systems except the bifilar the current passes through the electrode, the molten metal bath, and the solidified ingot. In the bifilar system, developed by the Soviets, current flows through one electrode and then through the slag to the second electrode--in essence a short-circuited connection through the slag layer. The bifilar system was developed to allow the ESR of large cross-section ingots and in particular square and slab ingots without an increase in transformer power. Two electrodes are connected in series in a single-phase a-c system which allows the use of shorter electrodes and leads with a resultant decrease in inductance losses. Typical reductions are shown in Table 2.

TABLE 2. COMPARISON OF THE ESR PROCESS USING SINGLE ELECTRODE AND BIFILAR SINGLE PHASE A-C SYSTEMS[8]

Melts	Type of Circuit	Transformer		Production Rate, kg/hr	Power Consumption, kWh/ton
		Voltage	Amperage		
1	Single	48	1200	22.8	2500
2	Bifilar	48	1200	45.6	1200
3	Single	52	1200	42.6	1620
4	Bifilar	52	1200	84.0	860

Another method of reducing inductive power loss is to operate at lower frequencies, e.g., 2-10 hertz. This approach, however, requires a separate transformer for each electrode. For example, in a 4-electrode system four transformers would be required. In the bifilar system 4 electrodes would require two transformers. Both systems are protected by patents and licenses are issued to firms utilizing them. The bifilar system is patented by the Paton Institute, Kiev, USSR, and the use of low frequencies by the Böhler Brothers Company, Kapfenberg, Austria.

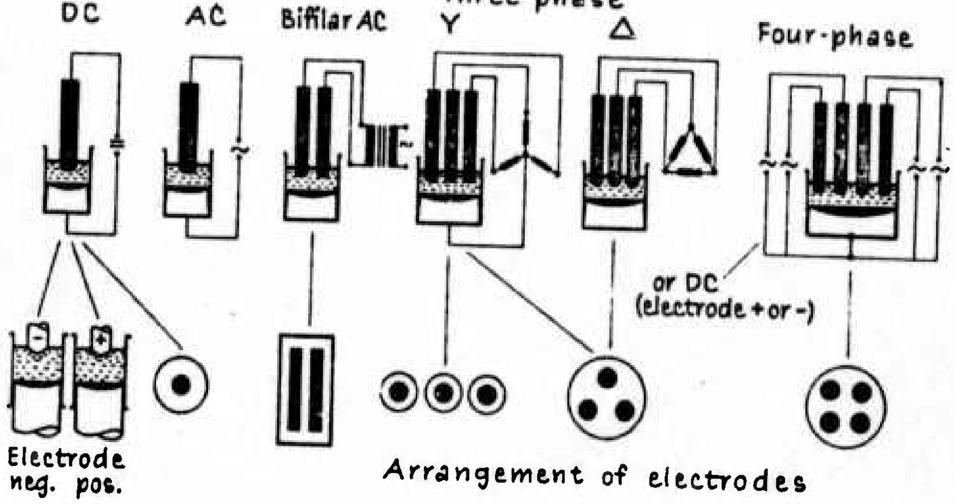

FIGURE 2. ELECTRICAL SWITCHING OF ESR FURNACES (6)

Three-phase a-c systems are more efficient from the standpoint of balanced power supply lines (bus bar loading). However, three-phase a-c is not amenable to the production of square or slab ingots. In addition, longer electrodes are usually required, which can introduce metallurgical problems in the production of the electrodes.

Furnace Design. There are six major designers of ESR furnaces at the present time. Paton Institute (USSR), Böhler Brothers (Austria), Leybold-Heraeus (West Germany), Consarc (U.S.) Birlec Ltd. (England), and recently ULVAC (Japan). Each firm has its own individual preferences. At the present time there are about 72 ESR furnaces in the Free World, either operating or under construction, that can produce ingots 16 inches (400 mm) or larger in diameter. These furnaces are distributed among the major designers and manufacturers in approximately the following pattern: Paton Institute - 6, Böhler - 19, Leybold-Heraeus - 8, Consarc - 15, Birlec - 12, and ULVAC 1 (a 40-ton slab furnace, under license from Paton Institute). Some 9 furnaces were self made by the users, and 2 were made by ASEA (Sweden).

Each company has its own specific design preferences. The high degree of flexibility of the ESR process allows various arrangements of electrodes, design of molds, and product shapes. For instance, both the ingot and the mold may be stationary, or the ingot may be stationary and the mold movable, or the ingot may be movable while the mold is stationary. (In the latter case, the ingot is withdrawn from the bottom of the mold.) Product shapes include round, square, and slab ingots, hollow ingots and semifinished parts such as crankshafts, large valves, rolls, large rings, vessels, and various complex components such as shown in Figure 3.

Quality of ESR Product. Metals produced by the ESR process exhibit high levels of purity, low levels of microsegregation, and uniformity of composition which yield high levels of toughness, improved workability, and weldability. The comparison of the high-purity, essentially inclusion free ESR metals with those conventionally melted is dramatic. For example, as shown in Figure 4 the segregation of elements in large steel ingots is significantly lower than those produced by conventional methods. Uniformity of composition (a low degree of segregation) means uniformity of mechanical properties. Figure 5 shows another example of the high level of compositional uniformity in a large ingot 51 inches (1300 mm) in diameter.

The inherent toughness of weldments in as-cast ESR steel relative to that of weldments in rolled plate prepared from conventionally melted steel is shown in Figure 6. In a similar vein is the comparison of impact toughness between conventionally melted and ESR structural steel shown in Figure 7. A general summation of the effects of ESR on the properties of steel is given in Figure 8.

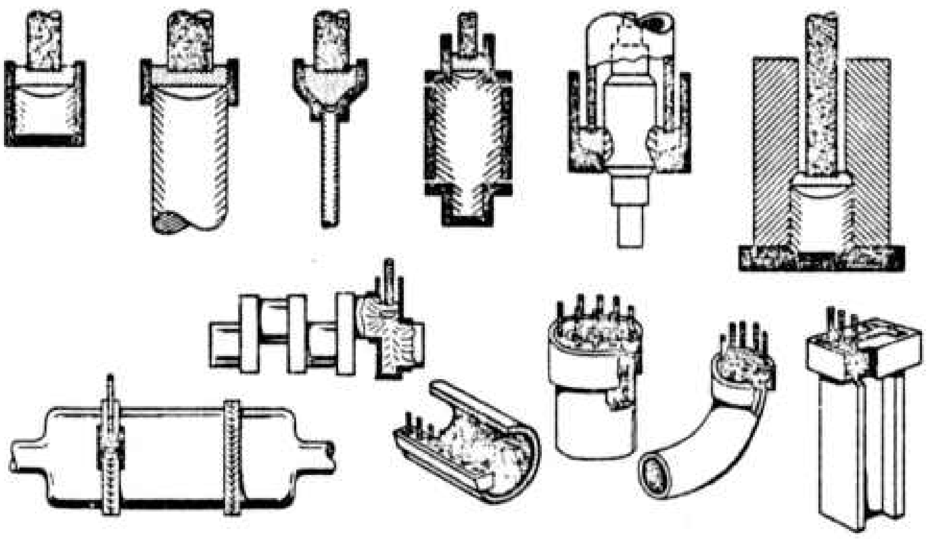

FIGURE 3. METHODS USED TO PRODUCE VARIOUS SHAPES BY ESR[9]

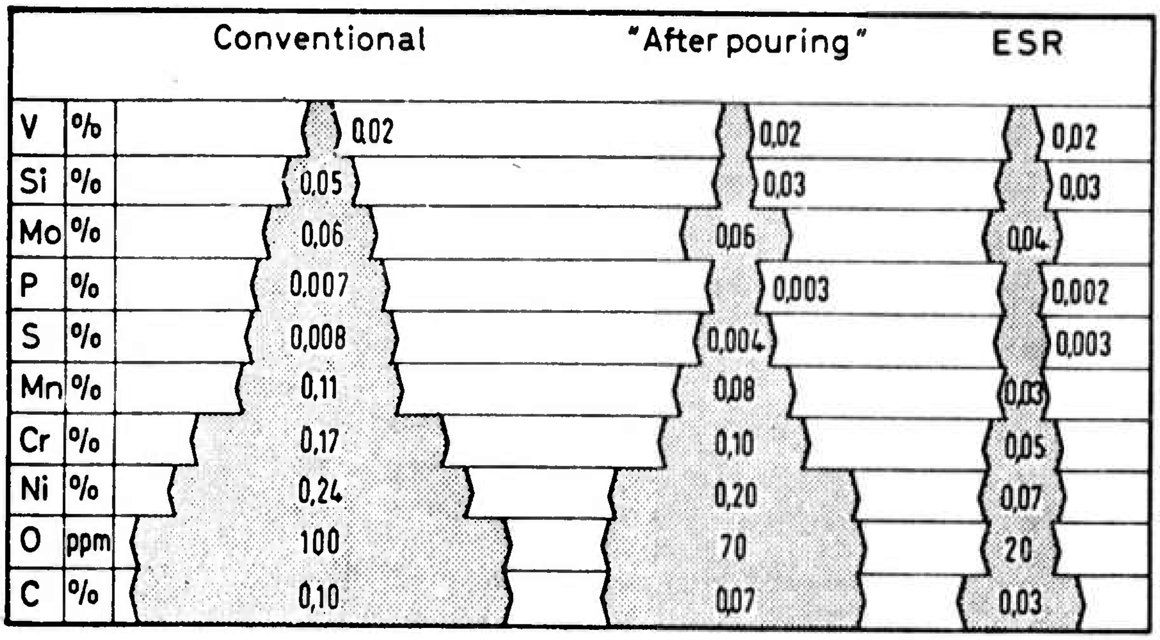

FIGURE 4. INGOT SEGREGATION IN 70-TON INGOTS ("AFTER-POURING" IS A JAPANESE TREATMENT OF CONVENTIONALLY MELTED STEEL TO REDUCE SEGREGATION)[11]

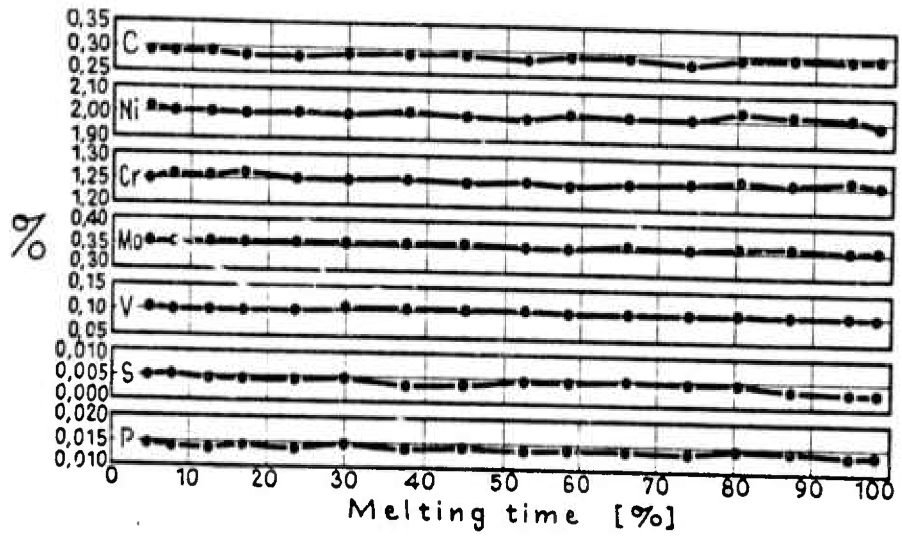

FIGURE 5. THE VARIATION OF ELEMENTS DURING ESR OF A 51-INCH (1300 MM) DIAMETER INGOT[9]

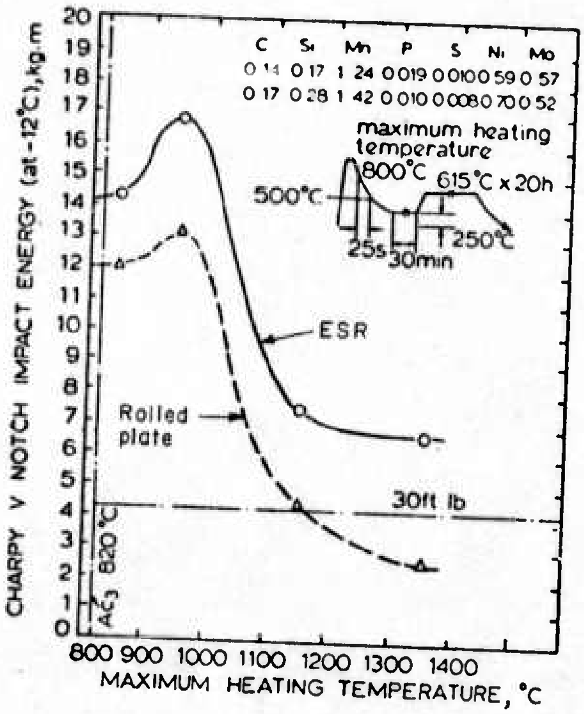

FIGURE 6. EFFECT OF HEAT TREATMENT OF THE HEAT-AFFECTED ZONE OF WELDMENTS ON IMPACT STRENGTH(13)

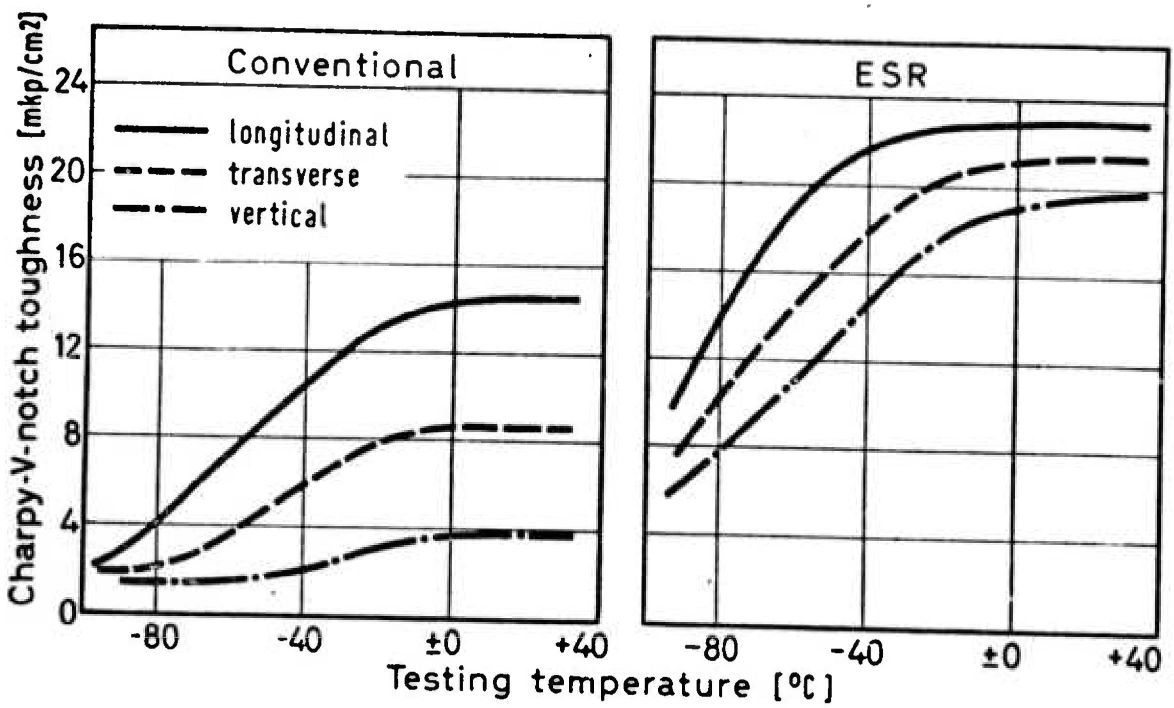

FIGURE 7. THE EFFECT OF MELTING METHOD ON THE IMPACT STRENGTH OF A FINE-GRAINED STRUCTURAL STEEL 1-INCH (25 MM) THICK[11]

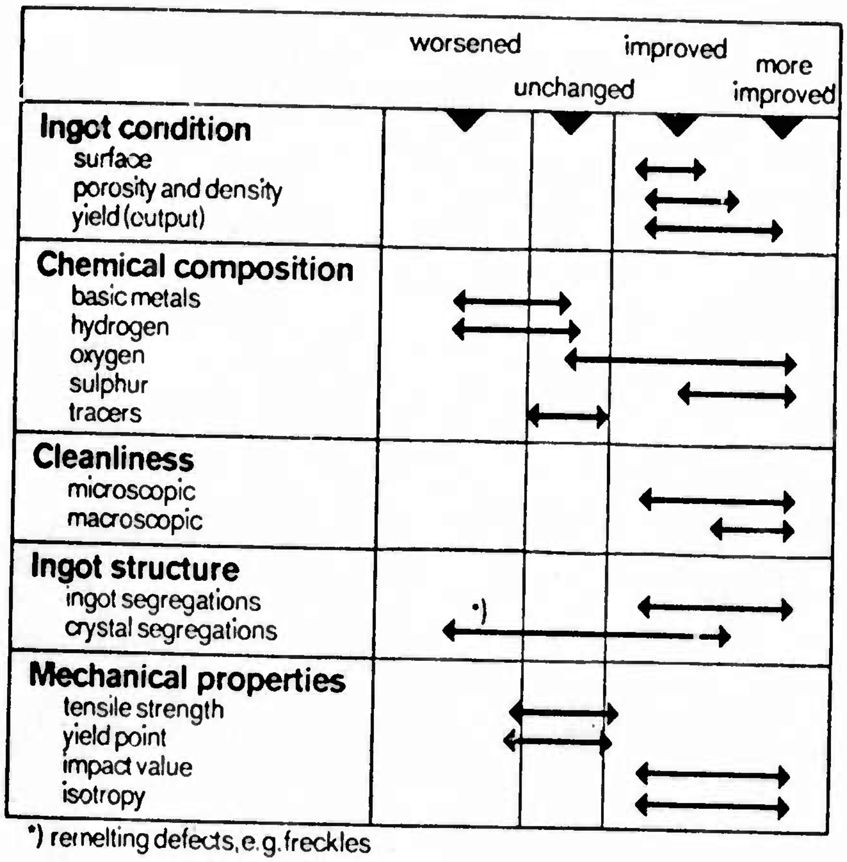

FIGURE 8. THE INFLUENCE OF ELECTROSLAG REMELTING ON PROPERTIES (11)

Economics. The ESR process is a remelting process, which inherently implies higher costs. In addition the ESR process is more energy intensive than is conventional melting, so the actual remelting costs are higher. On the credit side of the ledger, not considering improved mechanical properties as a factor, higher ingot yields are achieved with ESR than with conventionally melted ingot. In ingot weights up to about 100 tons the increase in yield on forging-steel grades is about 15 percent. (In other alloys such as nickel-base alloys the increase in ingot yield could be as high as 40 or 50 percent.) Rejected material is also appreciably less, often 50 percent less. Ingot surface is generally of high enough quality that the ingot can be worked (rolled, forged, etc.) without prior conditioning. These factors decrease the negative effect of the remelting costs.

An example of a 4.6-ton rotor for an electric power generator forged from a 3 percent nickel steel shows that an ESR rotor can be produced for the same cost as a rotor conventionally melted, as shown in Figure 9.

Other advantages favoring ESR steel is its ease of working. For example, greater forging reductions can be made with a subsequent decrease in the number of heating cycles and forging time. This savings in forging cost for large ingots can be as high as 45 percent.

At the present time, however, ESR is primarily utilized and under consideration where the resultant improved properties justify the additional cost of remelting. As the design community becomes more aware of the potential savings that can be realized with ESR the presently increasing demand will accelerate at an even faster rate.

Industrial Applications for the Technology

The present industrial uses of ESR metal cover a wide range of applications and the scope of these uses is constantly expanding. Industrial application of a process is closely related to economics. In short, the question is whether a product can be made with some specific process at a lower unit cost than when another process is used. Unit cost in the last analysis includes all of the cost of production such as rejects, amount of materials consumed, labor, power, etc. In the previous example of the unit cost for producing a 4.6-ton rotor these factors were presented. This is the example of producing a better product with no increase in unit cost, and would be the preferred method of production. ESR, of course, finds ready application where the unique combination of characteristics it produces is required and cannot be achieved using a cheaper, alternate method. The present applications that fall into these categories are as follows:

Conventional				E S R
DM 10,836	12 t*)	Crude steel input	8,8 t**)	7,242 DM
120	10 DM/t	Vacuum treatment	Tap degassing 10 DM/t	88
-		Remelting costs	400 DM/t	3,520
- 1,382	4,164 t	Credit for scrap discard	0,864 t	- 320
9,574	8,4 t	Raw forging ingot	8,4 t	10,530
3,000		Forging, heat treatment		3,000
12,574	7,5 t	Forging weight	7,5 t	13,530
6,400		Machining, quality control		6,400
18,974	4,6 t	Finished weight	4,6 t	19,930
2,087	11%	Reject quota	5,5%	1,096
21,061		MANUFACTURING COSTS		21,026

*) Electro steel, double slag   **) Electro steel, one slag

FIGURE 9. COST COMPARISON OF 4.6-TON ROTORS FABRICATED FROM VACUUM DEGASSED AND ESR 3 PERCENT NICKEL STEEL(9)

DM = Deutsche Mark.

- Produces a better product with no significant increase in cost

Rolls for Cold Rolling. The use of ESR produces rolls with a superior surface finish with a 50 percent decrease in grinding to finish the rolls.

Rotors. Higher levels of toughness and low levels of microsegregation have raised significantly the safety factor over that achieved with conventionally melted steel. In time, this situation will lead to a reduction in weight in rotors by raising the strength level. Several types of rotors are involved, e.g., generator rotors and gas-turbine-engine rotors.

Turbine Discs. The situation here is similar to that of rotors.

Tool and Die Steels. The tool and die steel field is being taken over rapidly by the ESR process. Better quality material is produced compared to conventionally melted materials without a large increase in cost. Higher ingot yields and lower amounts of rejects are the primary positive factors dictating the change to ESR.

Nickel-Base Alloys. The ESR process is making rapid inroads in the production of nickel-base alloys that were previously almost exclusively melted by the vacuum-arc remelting process. The use of ESR at the present time has been primarily in the melting of nickel-base alloys with low amounts of easily oxidized elements. The high ingot yields, good ingot surface, and the ability to form ingot shapes such as squares or rectangular slabs are the principal attractions.

Torsion Bars. The large increases in endurance limit and the ability to utilize higher strength levels has caused ESR steel to essentially replace conventional steel. The cost of material is a relatively small part of the total cost.

- Applications where the use of ESR is required or improved properties are realized, generally at increased cost

  Very Large Rotors for Large Power Generators. At the present no other system is available for producing very large high-purity ingots, weighing 150 to 300 tons. The Rochling-Burbach ESR furnace in West Germany is capable of producing 165-ton ingots. Larger ingots will use some variation of the ESR process, e.g., (1) casting large conventional ingots, pushing out the inferior center portion, and remelting the center with ESR,(2) pouring a conventional ingot and using ESR as a means of hot topping, i.e., filling the center of the ingot during solidification, (3) electroslag welding several ESR ingots into a large ingot.

  Collander Rolls. The requirements for cleanliness and concentricity during operation of these heated rolls used for coating magnetic strip requires the use of high-purity steel. ESR rolls readily meet the requirements of maximum deviation in concentricity of 10 microns, because of their chemical homogeneity and isotropy of properties.

  Ball Bearings. Ball and roller bearings with superior performance characteristics are produced from ESR steel. Critical bearings specify ESR.

  High-Temperature Austenitic Steels. Improved creep and rupture properties are obtained with ESR. The degree of penetration of the market will depend upon the relationship between increased cost and improved properties.

  Soft Magnets. Higher uniformity of magnetic flux fields and induction values are obtained by ESR. The degree of market penetration will depend on the relationship between increased cost and improved properties.

  Texas Towers. Structural applications of this type involving severe and complex loading will require the higher toughness characteristics available in steel made by ESR in the most critical components.

Pressure Vessels. ESR steels are now being incorporated into the design of nuclear pressure vessel assemblies where high reliability and integrity are necessary.

Ultrahigh-Strength Steels. ESR steels are finding increasing use in applications utilizing steels at high-strength levels. For example, the landing gears of the Concorde supersonic transport are fabricated from ESR steel. The inherent high levels of toughness and high uniformity of properties in all directions (isotropy) will rapidly increase the number of applications in this area and the quantity of ESR steel used.

The Production of ESR Castings. A number of ESR castings are presently being produced in the USSR and Japan. These include large marine crankshafts, large valves, tires for large cement kilns, hollow ingots, large connecting rods, and complexly shaped pipe and tubing. The mechanical properties of as-cast ESR steel are equal or superior to those of conventionally melted rolled material.

Based on discussions with a large number of people involved in commercial ESR melting in the U.S., Europe, and Japan, it is anticipated that all of the above applications will significantly penetrate the market by 1990. Tool and die steels, rotors, rolls, stainless steels, and nickel-base alloys are areas where ESR presently has penetrated the market and its share of the market will continue to expand. The use of ESR material in highly, complexly loaded structural members such as the critical portions of Texas Towers, pressure vessels, and pressure-vessel components for nuclear power stations, and castings is not at present widespread. Such uses are expected to expand rapidly in the next 15 years.

Projected Market Penetration by 1990 and Requirements for Critical Materials

Market Penetration. The projected market penetration through 1990 can be expressed in terms of ESR metal production. In 1973, about 100,000 tons of ESR metal was melted in the Free World. It is estimated that between 180,000 and 200,000 tons will be melted in 1975. By 1980-1985 it is estimated that Free World production will reach 500,000-700,000 tons, and by 1990 over 1,000,000 tons.[10,11,14-16] These estimates are based upon industrial applications for ESR metal. Consideration of potential military usage in applications such as gun tubes, armor, and ship plate could easily raise the estimates of production in 1990 to over 1,500,000 tons.

Production figures in the USSR are not readily attainable. However, in 1973 the Soviets reported a production of about 500,000 tons with 1,000,000 tons planned for 1975-1976. On this basis Soviet production in 1990 could be conservatively estimated at well over 2,000,000 tons.

Critical Materials. The ESR process does not utilize critical materials per se; it is a process for the conversion of metal to a higher quality product. Consequently, it can be used to melt essentially all types of metals that possess varying degrees of criticality. At the present time, however, the availability of ESR capacity in the U.S. is a critical problem. For example, the U.S. has only one ESR unit for the production of slab ingot; this is owned by the Lukens Steel Company. This situation has already lead to shortages. For example, exploitation of DoD applications, such as armor, has been retarded significantly because of the shortage of ESR plate. We are presently dependent upon foreign sources of supply for ESR plate. In this regard, the Japense and British are planning to at least partially fill the need for ESR slab ingot and plate. Tonnage requirements for ESR metal in the U.S. by 1990 are estimated at 500,000-700,000 tons; this includes metal for both industrial and military applications. At the present rate of growth U.S. capacity will not be able to satisfy this estimated requirement.

At the present time U.S. capacity for the production of ESR metal is in the order of 70,000 tons, and of this more than half of the capacity is for the production of tool and die steels. To meet an estimated requirement of 500,000 to 700,000 tons of ESR metal by 1990, and increase in capacity of 7 to 10 fold would be required.

In anticipation of this requirement, the Nippon Steel Company of Japan has in operation an ESR furnace producing 40-ton slab ingot with an eye to capturing part of the U.S. market.(17,18) The British Steel Corporation, following the same path of action, is building a 50-ton ESR slab ingot unit which will be completed in January, 1976.(19) Even with the production from these two foreign facilities the U.S. would still need a 5 to 7 fold increase in capacity.

Department of Defense Requirements

The entry of ESR steel into the defense community has instigated research and development activities, and in some instance production of components, throughout the world. It is reasonable to expect that within a short span of time, 5 years, most military gun tubes in the world likely will be fabricated from ESR steel. The increase in fatigue life is of such magnitude in comparison with conventionally

melted steels that ESR can be specified on the basis of safety alone. In addition, however, the availability of steel with these improved properties will allow designers to increase gun pressures and increase the strength level of gun tubes with a resultant increase in gun performance and a possible decrease in tube weight. At present it is believed that all of the major powers except the U.S. are producing ESR gun tubes, and the U.S. has an active development program in progress. Among the smaller countries Italy, Spain, and the Union of South Africa have purchased ESR furnaces primarily for the production of gun tubes. It is believed that the USSR has been producing ESR gun tubes for some period of time.

Armor plate is another area where the use of ESR steel shows great potential. The inherently high levels of toughness in ESR steels will allow the development of armor with improved resistance to ballistic penetration. Ship plate, and in particular submarine hulls, is an area where ESR steels will significantly improve the product. In addition to these potential uses for ESR steel, there are a number of structural applications in aircraft and vehicles where the properties available in ESR steel will be required. Applications such as landing gears, structural support in wing and fuselage assemblies, torsion bars, missile casings, helicopter rotors--essentially all high-strength highly stressed components are strong candidates for ESR metal.

Potential Procurement and Development Problem Areas for the Department of Defense

The potential problem area for DoD will be in the availability of sufficient capacity in the U.S. to fulfill possible requirements, as outlined in the previous section. Foreign sources of production capacity are not usually considered viable for vital DoD requirements. The seriousness of the present situation is emphasized by the fact that military research and development (e.g., on armor plate) already has been curtailed because of a lack of ESR material. The lack of ESR capacity will probably delay the incorporation of ESR steel into major U.S. military systems. For instance, at present there is only one ESR facility in the U.S. for the production of slab ingots; the production capacity of this unit is understood to be fully committed to nonmilitary products.

Fiber-Reinforced Composites

by

Bryan R. Noton

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Technical Description of the Technology

Composite materials are systems resulting from the assembly of two or more materials, i.e., a filler or reinforcing fiber in a resin, metal, or ceramic matrix, in which the proportions and orientations of the reinforcing materials are tailored to provide desired properties and characteristics. There are three general classifications of composites. There are fibrous, laminar, and particulate composites. Fibrous composites consist of fibers in a matrix; laminar composites consist of layers of composite, metallic, or other materials, and particulate composites consist of flake or skeletal particles in a matrix.

The development of engineered composite materials began in 1938 when Owens-Corning Fiberglas Corporation was formed to manufacture fiberglass. On March 24, 1944, the Vultee BT-15 airplane, with a fuselage fabricated of composite materials, was first flown at Wright-Patterson Air Force Base, Dayton, Ohio. This fuselage was considered to be the first successful major structural component of an airplane using glass-reinforced plastics to be developed and flown. The wings for the North American AT-6 in this same period provide a further example of a successful R&D program in applying glass-reinforced plastics to aircraft. In 1946, glass-reinforced plastics began penetrating several nonmilitary markets which include boats, automobiles, trucks, construction, appliances, containers, electrical materials, furniture, plumbing, pipes, and tanks. The General Motors' Corvette entered production in 1953. In 1976 about 650 million pounds of glass-reinforced plastics are expected to be employed in the various sectors of land transportation. Further information on the markets for glass-reinforced plastics is provided in Table 3 .

The designer frequently classifies composite materials into two groups related to the performance. There are conventional composites, such as glass-fiber reinforced plastics, and also advanced composites, i.e., those with extremely high tensile strength and modulus-to-weight ratios, such as carbon-fiber reinforced epoxy and boron-fiber reinforced aluminum. However, in several important markets for composites, such as automobiles and aircraft, it is more appropriate to refer to low-cost and high-cost composites. This approach to referring to composites is preferable because cost has replaced performance and schedule in the design and development of many civilian and DoD systems. Low-cost composite materials refers to those priced significantly less than \$5/lb, and high-cost composites are those that cost well in excess of \$5/lb. If an expensive composite material is to be specified for a certain application,

TABLE 3. GLASS FIBER USAGE

Markets	(Volume in millions of pounds) 1970	1971	1976
Aircraft and space	28	25	40
Appliances and equipment	31	43	123
Construction	117	134	317
Consumer goods	69	80	122
Corrosion-resistant products	78	89	241
Electrical rods, tubes, parts	59	56	102
Marine and marine accessories	181	260	433
Land transportation	167	219	648
Other	67	72	149
Total	797	978	2175

Data supplied by Reinforced Plastics/Composite News Digest, Morrison-Gottlieb, Inc., New York (1973).

it will be necessary to justify its use either on the basis of cost-competitiveness or cost-effectiveness. Cost-competitiveness refers to the cost of the assembled and installed hardware, and cost-effectiveness is based on life-cycle costs, i.e., procurement, operation, maintenance, and scrap value.

An important design trend for both civilian and DoD systems to conserve materials and to reduce cost is to utilize hybridized composite systems, e.g., combinations of glass-, carbon-, and aramid-fiber reinforced plastics. The specific tensile properties (i.e., the tensile properties divided by the density) of these fibers are compared in Figure 10 with those of conventional metals. The cost-conscious procurement agencies can be expected to emphasize design-to-cost to an increasing extent. This goal will require innovative approaches when employing high-cost composites instead of the substitution of advanced composites for conventional materials in existing designs or at the detail design phase in the development of a system.

The use of both low-cost and high-cost composites will require realistic assessment of the total cost of fabricating hardware. The cost

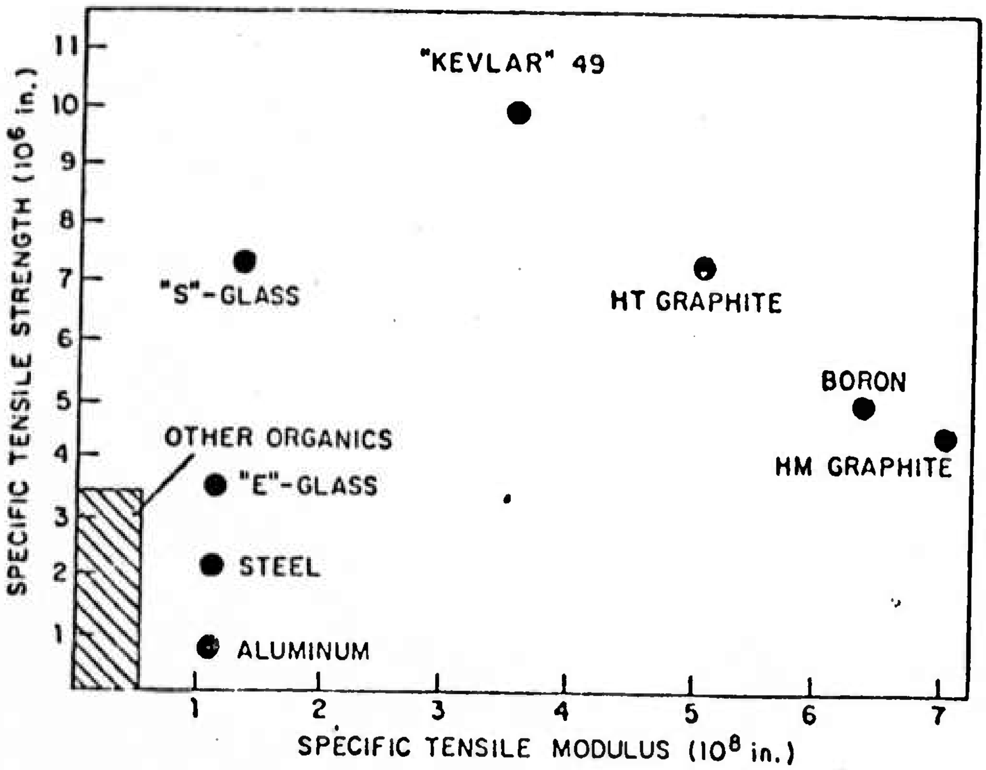

FIGURE 10. SPECIFIC TENSILE STRENGTH AND SPECIFIC TENSILE MODULUS OF REINFORCING FIBERS

must include hand-layup operations, quality control, and quality assurance. Successful and increased application of high-cost composites to DoD systems will be determined by the development of, firstly, design concepts which lend themselves to ease of fabrication and quality control, and secondly, automated fabrication processes to decrease fabrication cost. The market penetrations discussed later hinge on these developments.

The ability of the designer to tailor composite systems, within the limitations of fabrication cost, to respond to systems and component design goals, is the unique characteristic of composites. Combinations of various fibers are sometimes employed within a single composite element in order to reduce cost and/or optimize structural properties. Such systems of fibers are referred to as hybridized laminates or hybridized composites. By selecting fiber orientations for the lamina, combinations of strength and stiffness for various loading conditions can be achieved. Furthermore, composite materials can be applied to selectively and efficiently reinforce conventional materials, such as aluminum and wood, to not only conserve conventional materials, but also provide additional characteristics, such as fracture tolerance, to the structure.

Examples of some of the alternate fibers within this technology are listed in Table 4.

Industrial Applications for the Technology

The advanced composite materials with the most promising potential for commercial applications are graphite (pitch-based)/epoxy, aramid/epoxy, and boron/aluminum. Combinations of these fibers frequently provide opportunities to optimize designs. However, the use of high-modulus, high-strength fibers such as graphite can, in some cases, when combined with low-cost fibers, be justified on the basis of a reduced fabrication cost for the product. A thinner glass-fiber reinforced laminate can sometimes be used when selectively reinforced by a grid of graphite fibers and the reduction in labor costs can compensate for the cost of the graphite fiber.

Significant opportunities exist to selectively reinforce conventional materials with advanced composites to conserve materials while maintaining low manufacturing cost and providing fracture tolerance. Selective reinforcement represents the <u>first</u> phase in applying advanced composites in several markets and can be achieved with a minimum expenditure for research. Examples of this design approach are

- Unidirectional graphite/epoxy reinforced beams
- Unidirectional boron/epoxy reinforced aluminum shapes

TABLE 4. FIBER PROPERTIES[a]

Fiber	Modulus, 10^6 psi	Tensile Strength, ksi	Tensile Failure Strain %	Specific Gravity	Density, lb/in.^{3}	Cost $/lb	Cost $/in.^{3}
Boron, 4 mil	60	460	0.77	2.60	0.094	250.00	24.00
Graphite "Thornel" 300	34	380	1.07	1.74	0.063	50.00	3.15
"Kevlar" 49	19	400	1.75	1.45	0.052	8.50	0.44
"Kevlar" 29	9	400	3.8	1.45	0.052	7.50	0.39
E-Glass	10.5	250	2.4	2.54	0.092	0.50	0.05
S-Glass	12.5	450	3.6	2.48	0.090	12.00	1.08

(a) Table from Reference 20.

- Graphite-fiber grid in glass-reinforced plastic laminates
- Aluminum and titanium castings and forgings reinforced with various advanced composites.

Industrial Applications of Graphite/Epoxy. The primary reasons for employing graphite fibers are their high-modulus, high-strength, low-density, and low-cost potential. The secondary advantages are low thermal expansion, design flexibility, vibration damping, corrosion resistance, and wear resistance. Graphite fibers are used as continuous, chopped, and sized fibers, as ribbon and cloth, and in various forms which include prepreg tape, preplied sheets, pultrusions, and molding compounds.

Graphite/epoxy composites are being extensively employed for commercial products. However, due to a potential for lower cost fabrication, graphite/thermoplastics can be expected to make inroads into the markets. Advantages arising from such applications are not only that the increased volume of material required will reduce cost, but that mass-produced products will lead to the development of rapid fabrication methods which will benefit DoD system development and production.

Typical of the commercial products currently in production in the United States are

- Golf shafts
- Tennis rackets
- Fishing rods
- Fishing reels
- Javelins
- Skis
- Archery bows
- Hockey sticks.

Other potential commercial applications of graphite/epoxy composites are as follows (in most cases experimental products have been evaluated):

- Bicycles
- Boat hull and mast reinforcement
- Car panel reinforcement
- Push rods and rocker arms
- Prosthetic devices (arms and legs)

- Kayaks
- Gear wheels and bearings
- Transmission shafts
- Springs
- Flywheels
- Calipers
- Heddle frames of textile machines.

Industrial Applications for Aramid/Epoxy. E. I. du Pont de Nemours & Co., Inc., has developed and is marketing a series of aramid organic fibers trademarked as "Kevlar". Three types of this fiber are available; the one that is intended primarily for the reinforcement of plastics is known as "Kevlar" 49.[21] Applications of this fiber for this application are due primarily to the following properties:

- High specific strengths and stiffnesses
- Impact strength
- Durability
- Vibration damping.

Typical industrial applications, in combination with other reinforcements, are

- Canoes and kayaks
- Archery bows
- Arrows
- Hockey sticks
- Sailboat hulls.

Industrial Applications for Boron/Aluminum and Boron/Epoxy. The applications of boron fibers in an aluminum matrix mentioned in this section are due to the properties in Table 5 and the advantages listed below from Reference 22.

The advantages of boron/aluminum are of particular interest to the designer and are as follows:

- Extremely high compressive strength (>600 ksi)
- Bearing strength of aluminum matrix suggests simpler joints than for plastic matrices

- Fatigue life extensions (3-10 times that of conventional structures)
- Thermal conductivity of matrix
- Improved elevated-temperature properties
- Proven joining methods applicable.

TABLE 5. RELATIVE PROPERTIES COMPARED TO B/Al

	Titanium	Aluminum	Stainless Steel	B/Al
Modulus/Density	0.326	0.340	0.385	1.0
Strength/Density	0.417	0.218	0.402	1.0

The AVCO Systems Division, Lowell, Massachusetts, is pioneering applications of boron/aluminum in commercial markets. Examples of these products and manufacturers identified by AVCO are

- Tennis racket stiffeners (Manufacturer: Head Ski and Sportswear, Inc.)
- Ski poles (Manufacturer: AVCO)
- Skis (Manufacturer: AVCO)
- Fishing rods (Manufacturer: AVCO)
- Bicycle frames (Manufacturer: AVCO).

Potential important applications for boron/aluminum are for various components in transportation systems. Examples of these components in which the reduction of weight and inertia and the increasing acceleration of the component lead to further improvements throughout the vehicle are as follows:

- Connecting rods
- Valve stems
- Push rods
- Transmission shafts.

Weight savings is not the only advantage, however, of employing boron/aluminum. The Lockheed S3A aircraft wing box listed later was tested in fatigue and the fatigue life was 5 times the design life of 6,000 hours. Furthermore, because metal-matrix composites are more compatible with metalworking techniques and accepted joining methods, this compresses the transfer process for the boron/aluminum technology.

AVCO is also actively pursuing commercial applications of boron/epoxy materials. Examples of such applications are

- Golf club shafts
- Sailboat masts
- Bicycle frames
- Ski poles
- Skis
- Fishing rods.

Projected Market Penetration by 1990 and Requirements for Critical Materials

Graphite Fibers. Graphite fibers can be produced with a wide range of strengths and moduli of elasticity, as desired. Boron fibers lack this capability. Furthermore, boron fibers are less drapable than graphite, i.e., less able to conform to a small-radius curve without damage or excessive stress. It appears likely that graphite filaments will capture an increasingly large share of the total market for high-performance filaments; since production is now only a fraction of rated capacity, increased production should lower costs of graphite filaments and increase the number of end uses in which they will become competitive.

Graphite fibers are available in the form of yarn and two and are produced by the carbonization of various precursors: rayon, polyacrylonitrile (PAN), pitch (or lignite). The strength and stiffness is influenced by the heat-treatment temperature ranging from 2500-5000 F. Strength peaks when graphitization takes place around 2550-2900 F while Young's modulus keeps increasing as the graphitization temperature is increased.

While premium grade graphite fibers are today assumed to be required for aerospace products, it is possible that the increasingly severe design-to-cost environment may result in lower cost carbon fibers with the lower strengths and moduli being acceptable for, in particular, secondary structures which are significant cost drivers. Considerable interest is being focused on the development of fibers produced from pitch precursors. The low-cost potential of pitch fibers make them

attractive for many of the commercial applications listed earlier. The goal of the Union Carbide Corporation, developing pitch-based carbon fibers in the United States, is to reach an annual production level of 8 to 10 million pounds by 1981 with a product mix of low-cost materials, i.e., from short fibers costing $2 per pound, to woven fabrics costing $10 per pound in 1975 dollars.(23) Union Carbide Corporation is installing a pitch-precursor plant to respond to the production requirements to 1981 after which the plant will be expanded.(23) At present, Union Carbide markets graphite fibers produced by Toray Industries, Inc., of Japan.

In 1990, Union Carbide considers that a potentially realizable goal is 100 million pounds per year.(23,24) This projection is said to depend largely on the ability of new technology (e.g., pitch-precursor fibers) to decrease the cost of graphite fibers.(24) In 1974, it is estimated that 140,000 pounds of high-performance graphite fibers were sold in the United States.(24)

It is not expected that the carbon-fiber market will grow as that of glass fibers; the latter fibers cost approximately $0.50 per pound and in 1971 reached a volume of approximately 1 billion pounds in the United States and 2 billion pounds in the Free World. However, an important factor that will accelerate the growth of the graphite-fiber market is that many of the fabrication processes developed for glass-fiber reinforced plastics are directly applicable to the fabrication of hardware from graphite-fiber reinforced plastics.

Union Carbide Corporation has indicated that no significant problems exist regarding critical materials that will hinder the production of 100 million pounds of graphite fibers in 1990.(23) Nevertheless, polyacrylonitrile (PAN) and pitch are both petroleum derived and 2 pounds of PAN are required to manufacture 1 pound of carbon fibers. Graphite fibers could be produced from coal tar pitch. Union Carbide is very knowledgeable of pitch and its potential; pitch is used in several processes today.

The important point is that graphite fiber is an engineering material today that has been accepted in several DoD and commercial sectors. However, in order to meet projected 1990 demands without relying excessivly on foreign sources, significant additional U. S. manufacturing capacity may have to be installed.

<u>Boron Fibers.</u> The projected annual production of and demand for boron fibers in 1990 is approximately 200,000 pounds.(25) However, this forecast depends on many factors, i.e., applications, economic environment, etc. Boron fibers are available in diameters of 2, 4, 5.6, and 8 mils. Borsic*, a boron fiber with a silicon carbide coating, is

*Registered trademark of E. I. du Pont de Nemours Co., Inc.

available in diameters of 4.2 and 5.7 mils. While research is under way to produce boron fibers on a graphite-fiber substrate, boron fibers are currently produced using a tungsten wire as a substrate.

This projected 1990 production is ten times the 1975 production, which is expected to be about 20,000 pounds.[26] The 1975 production capacity is believed to be about 25,000 pounds.

In the production of boron fibers at an annual rate of 200,000 pounds, two potential problems exist.[25] These are firstly, the capacity of industry to produce the small-diameter tungsten wire and, secondly, the available capital for construction and installation of the production facilities for depositing boron on the tungsten-wire substrate. For the production level cited, the capital cost of these facilities is expected to be $50 per pound of annual production capacity.[25] Thus, it is possible that production capacity will be inadequate to meet demand in 1990.

Although the price of boron fibers is expected to decrease in the future, it will be necessary to carefully select potential applications in which, firstly, the material is cost-effective based on life-cycle costs, secondly, where the benefits of specifying boron/aluminum for the component cascades throughout the design, and thirdly, the material is introduced innovatively at the conceptual design phase of the system development and not later at the detail design phase, where form, fit, and function requirements must be satisfied. The current and projected prices of boron fibers are as follows, in 1975 dollars.[25]

	Year		
Fiber Diameter	1975	1980*	2000**
Large (8 mils)	$150/lb	$ 75/lb	$40/lb
Small (4 mils)	$250/lb	$125/lb	$60/lb

Boron fiber is an accepted engineering material and is in production for tubular members for the NASA Space-Shuttle fuselage competing with riveted aluminum.

Aramid Fibers. A further fiber which is being accepted on an increasing scale as an engineering material is the aramid organic fiber known as Kevlar-49***, which is manufactured by E. I. du Pont de Nemours Co., Inc.[27] Du Pont is installing a commercial plant in Richmond,

*Assuming an annual production of 100,000 pounds/year.
**Assuming an annual production of 1 million pounds/year.
***Registered trademark of E. I. du Pont de Nemours Co., Inc.

Virginia, that may, within 2 years, have an annual capacity of 50 million pounds of "Kevlar" fibers. Present production capacity of the plant is 4 to 5 million pounds. While the process is more complex than for polyester or nylon fibers, the plant is flexible and can produce the three types of "Kevlar" fibers. The equipment required for each type is essentially the same and no problems are foreseen. This is important because it enables Du Pont to rapidly respond to DoD and industrial requirements. Due to uncertain economic conditions, it is not possible for Du Pont to forecast the 1990 volume requirements, but in 1980 the goal is to produce 30 to 50 million pounds of "Kevlar" fibers per year. However, a large percentage of this volume is expected to be the type of "Kevlar" fiber that is used in the manufacture of tires, rather than "Kevlar"-49 for the reinforcement of plastics.[27]

The approximate selling prices of "Kevlar"-49 fibers in 1975 and 1980 are \$8/lb and \$4/lb, respectively.

"Kevlar" products are based on petroleum. The weight of raw material per pound of "Kevlar" was not released by Du Pont.

Other Composites. A number of fibrous composites are presently in the experimental phase of development and cannot be realistically discussed with regard to projected tonnages in 1990 or critical material problems. Examples of such emerging materials are graphite/aluminum, boron/titanium, and beryllium/titanium. It will be necessary to develop, firstly, design configurations which lend themselves to ease of fabrication and, secondly, lower cost fabrication processes. As these materials are expensive the applications are limited, and high-cost fabrication processes further hinder the rapid development of these and similar materials.

For example, considerable interest is being focused on the emerging graphite/aluminum composite materials. The total electrical power required from the fabrication of graphite fibers to the assembly and installation of the composite component or structure is approximately one-half that needed when aluminum alone is used. Provided that research programs adequately address the problem areas listed later, graphite/aluminum composites have the potential to drastically reduce, in the 1990's, the consumption of aluminum, while providing other advantages. The following are published properties[28] of this composite in wire form

Density--0.084 to 0.086 lb/in.^{3}

Graphite fiber content--30 to 37.5 volume percent

Tensile strength--90 to 110,000 psi

Tensile modulus--20 to 25 x 10^6 psi.

The improvement in the tensile strength and modulus of aluminum are signficant, e.g., the modulus of aluminum alloys is approximately 10 x 10^6 psi.

The problem areas requiring research before this material will be considered seriously by engineering designers for industrial and DoD applications are

- Fiber/matrix interactions
- Corrosive behavior in aggressive environments
- Improvement of transverse strength and reduction of scatter
- Optimization of graphite fiber and aluminum alloy combinations
- Correlation of hot-pressing parameters, i.e., time, temperature, and pressure, with mechanical properties
- Determination of impact properties, debris resistance, etc.
- Thermoelastic behavior, including residual stresses, of various combinations of fibers and alloys
- Thermal-cycling effects
- Laminate developments with aluminum and titanium interleaves
- Large-scale manufacture to reduce processing costs.

Engineering designers are expressing interest in the potential of graphite/aluminum because of the several important characteristics which justify research on the previously mentioned topics. These characteristics are summarized as follows:

- Low-cost potential of constituent materials
- Specific tensile strength and modulus are improved over those of conventional aluminum alloys
- The bearing strengths of the aluminum matrix suggests simpler joints than when using plastic matrices
- Fatigue properties offer improvements in product lifetimes, safety, and maintenance costs
- Graphite fibers improve the elevated-temperature capability of aluminum alloys
- The thermal conductivity of the metal matrix is important for some potential applications

- Easily sawn, machined, and drilled using conventional equipment
- Proven joining methods are applicable, i.e., mechanical fastening, adhesive-bonding, and rivet bonding.

Department of Defense Requirements

Boron fiber reinforced epoxy composites have attained production status for major components of both the Grumman F-14 and the McDonnell Aircraft Company F-15 aircraft. On the F-14, the horizontal stabilizer employs boron/epoxy skins, titanium splice plates, steel pivot, and an aluminum honeycomb core. The weight saving is 19 percent, i.e., 182 lb per aircraft, and this represents the first application of boron/epoxy. In a full-scale test, the fatigue life exceeded 2-1/2 times the requirement and failure was only detected in the steel pivot. The production versions of the vertical and horizontal stabilizers of the F-15 employ boron/epoxy skins on an aluminum honeycomb core. While no engineering data are available, the estimated weight savings is 22 percent.

On the new General Dynamics lightweight fighter, the YF-16, graphite/epoxy is used for the skins of the stabilizer.

It is important to note that boron/epoxy and graphite/epoxy structures, such as stabilizers, can frequently be produced at equivalent or lower cost than can titanium structures. This is because the principal of fabricating composite structures is to build up to shape, whereas with high-performance metallic structures utilizing forgings, the structure is machined down to shape. With composites, scrap material seldom exceeds 10-15 percent. In the case of titanium structures, scrap can exceed 70 percent and the cost of machining and the associated power requirements are excessive. Due to material wastage, the total cost of the titanium material used can exceed that of an advanced composite at today's prices.

Further applications of boron/epoxy in aerospace include the following:

- Lockheed C5A leading edge slat providing a weight savings of 21 percent; evaluated in service
- McDonnell F-4 rudder providing a weight savings of 36 percent; evaluated in service (51,000 hours)
- Sikorsky CH-54B helicopter tail-cone providing a weight savings of 70 percent; evaluated in service.

Besides primary structural applications of graphite/epoxy composites, the Rockwell International B-1 offers an excellent example of applications to secondary structure; these are reviewed in Reference 29. The applications include fuselage access doors, pivot fairings, wing-tip panels, spoiler panels, rudder, trailing edge, leading edge slats, weapon bay doors, wing gloves, and landing gear doors. The graphite/epoxy wing fairing provides an example of the savings versus aluminum, which are

Weight savings, 26 percent

Saving in initial cost, 31 percent.

All-flying (movable) horizontal stabilizers on various military aircraft are examples of highly loaded primary structures using plastic matrices. Landing gear tubular members and outer wings have potential in the near future. Three major problems with advanced structures are, firstly, the frequent dependence on hand-layup methods, secondly, the cost of quality control and quality assurance, and thirdly, the stretched-out production schedules and limited buys.

Helicopter rotor blades, transmission shafts, and landing-gear members are important opportunities for graphite/epoxies and hybridized composites.

Boron/aluminum is a promising engineering material and has been committed to production on the NASA Space Shuttle for a truss structure in the fuselage. Tubes produced by hot isostatic pressing and with 0° fiber orientation replace the conventional concept of riveted extrusion stiffened aluminum sheets. The compressive strength of boron/aluminum can exceed 600 ksi. Compressive strength is an important property for many aerospace applications such as wing upper surface panels and spar caps.

Other applications for boron/aluminum currently under evaluation are

- Longeron for the Rockwell International B-1
- Plate for the vertical fin of the McDonnell-Douglas DC-10 (to rapidly achieve flight experience for DoD applications)
- Guided air vehicle drag fins
- Rib for the Rockwell International B-1
- Panels for the Lockheed YF-12
- Electronic shelves for the NASA Space Shuttle
- Wing box for the Lockheed S3A aircraft

- Tubular landing-gear struts for the Vought A-7
- Canard lifting surface for a supersonic aircraft.

DoD uses for aramid (Kevlar)/epoxy composites in aircraft are as follows:(21)

- Interiors
- Floor panels
- Cargo liners
- Fairings
- Control surfaces
- Turbine-blade containment
- Doors and access panels
- Radomes
- Drone components
- Tooling for graphite parts
- Spacecraft antennas
- C4 motor cases.

Stated DoD uses for aramid (Kevlar)-graphite hybridized composites are as follows:(21)

- Helicopter fuselages
- Helicopter rotor blades
- Helicopter drive shafts
- Jet engine fan blades.

Moreover, aramid (Kevlar) fibers are being considered for ballistic and other protective apparel due to the following characteristics:

- Puncture and cut resistance
- Flame and heat resistance
- Light weight.

Such applications are as follows:

- Bullet-proof vest
- Flak vests
- Helmets

- Bomb disposal blankets
- Armored vehicles
- Hunting coats.

Potential Procurement and Development Problem Areas for the Department of Defense

In order for composite materials to achieve many of the potential DoD applications mentioned earlier, considerable attention must be given to the following areas:

- Development of economical automated fabrication methods for composite structures, to avoid hand operations. High fabrication cost is probably the major impediment to the large-scale use of composite materials. The automation of layup operations should greatly improve the economic situation. However, at present the production volume of machines that automatically lay tapes to form composite bodies and to selectively reinforce structures is quite limited.[29] To date, expensive sophisticated machines have been developed for each particular application. The tendency from now on will be to develop less expensive, simpler machines that can form specific geometrical shapes that have many applications.[29]
- Development of more economical boron fibers in which the substrate is a graphite fiber rather than a tungsten wire. The use of graphite fibers is expected to have two cost advantages. First, graphite fibers will be less expensive than tungsten wire. Second, the reactor (where the boron coating is applied to the substrate by chemical vapor deposition) can be run faster when graphite fibers are used than when tungsten wire is used, with no increase in labor requirement.[30] Because of these cost advantages, it is projected that the use of graphite fiber as the substrate would decrease the cost of boron/epoxy prepreg tape from the current price of about \$160/lb to about \$65-\$70/lb.[30]
- Development of innovative approaches at the conceptual-design phase of systems development (the brief "window of opportunity")
- Accurate assessment of cost/performance trades in the increasingly severe "design-to-cost" environment.

Superconductors for Power Applications

by

Frank J. Jelinek

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Technical Description of the Technology

Superconductivity had its start in 1911 through the work of Kammerlingh Onnes at Leiden. In an effort to obtain low-temperature resistivity data on pure mercury, he observed that the resistance dropped apparently to zero, rather abruptly at a temperature of approximately 4.2 K. The temperature at which the resistance drops is called the transition temperature, labeled T_c; the material is considered to be in the superconducting state below T_c and in the normal state above T_c. Superconductivity can be classified as a true thermodynamic state which is characterized by infinite electrical conductivity and perfect diamagnetism.

Since that time many materials have been discovered which undergo a superconducting transition. Several compounds, designated A-15 intermetallic compounds, exhibit the highest known transition temperatures (e.g., Nb_3Sn, T_c = 18.7 K; Nb_3Ge, T_c = >22K).

Some superconductors are able to carry large currents in high magnetic fields. This, of course, leads directly to the possibility of superconducting solenoids and any other applications that depend on high magnetic fields, such as transformers and high-torque motors. Superconducting solenoids have been considered almost since the discovery of superconductivity. However, no solenoids capable of producing magnetic fields greater than a few hundred gauss were made until 1960 when Autler of Lincoln Laboratory wound a solenoid from niobium wire and produced a field of a few thousand gauss. At the New York Physical Society Meeting in 1961, Kunzler of Bell Telephone Laboratories, reported that an intermetallic compound of niobium and tin, Nb_3Sn, has a critical field at 0 K, H_o, that may be as high as several hundred thousand gauss. Subsequently, niobium-zirconium alloys and V_3Ga being on the order of 500,000 to 800,000 gauss, and H_o for Nb-25 percent Zr being somewhat over 100,000 gauss.

Solenoids of niobium-zirconium alloys have been made to produce fields of over 60,000 gauss, and the Nb_3Sn solenoids to produce fields of over 70,000 gauss. This is quite remarkable in that the physical size of these solenoids is on the order of a few pounds and they require little in the way of power. For the same magnetic field strength, conventional solenoids of copper have very large power and cooling requirements, and for ordinary iron-core magnets, in addition to the power and cooling requirements, the weight may be on the order of 50 tons. This latter development, that is superconducting solenoids or materials

capable of carrying large currents in high magnetic fields, has led to most of the recent activity in the field of superconductivity. At present there is a large materials effort to find other systems with high current-high field characteristics. There is also a large effort under way to understand why these materials can support high magnetic fields and currents, and how they can be practically utilized in various energy schemes.

Industrial Applications for the Technology

Several energy generation, and transmission, and storage systems have been devised to take advantage of the unique properties and operating behavior of superconducting materials. These systems primarily include the following:

- Superconducting power generation (a-c electrical power generators and a-c and d-c motors)
- Superconducting power transmission (ac and dc)
- Controlled thermonuclear fusion and magneto-hydrodynamics, using superconducting magnets for plasma confinement.
- Inductive energy storage using superconducting coils.

All of these systems are in various stages of development. Superconducting power generation and transmission are the farthest advanced and are expected to impact the commercial market before 1990. Significant progress is expected in the areas of energy storage and controlled thermonuclear fusion; however, with the exception of small (100 MW) energy storage units, no industrial or commercial use is expected prior to 1990.

The following paragraphs describe briefly each of the four major applications areas.

Superconducting Power Generation. Because of the ever existing problem of weight and size considerations, superconducting rotating electrical machines were first conceived and introduced for various military applications. On-board, in-flight power generators are of significant interest to the Air Force, while the U.S. Navy is concentrating on superconducting motors for ship propulsion. Both of these specific applications of superconductor technology should be available in the next 10 years.

These military applications have been incentives to commercial development of power generators. MIT has developed a 2 to 3 MVA superconducting generator. The superconducting field coils are rotated in

liquid helium inside the armature which has normal windings. Westinghouse has since developed a 5 MVA machine for the Air Force which is now under test.

Currently under way are plans to build a 100 MVA superconducting generator.(31) This machine will have commercial value as a synchronous condenser to provide variable capacitive and inductive reactance, which provides phase regulation for long distance a-c transmission. The next level, expected prior to 1990, is the development of 500-600 MVA superconducting generators which are expected to provide serious competition, from a cost and operating standpoint, for conventional methods currently employed. The primary advantages of using superconducting coils in power generation is the ability to carry very large current densities with no I^2R dissipation.

AC synchronous machines are expected to impact the market by 1990, principally for large central-station generators.(32) A 2000 MVA machine has been designed. The superconducting field winding is carried in the rotor and is surrounded by at least two shielding cylinders, first the damper shield, which interrupts AC fields, serves as a damper, and absorbs forces due to terminal short circuits, and second, the cryogenic shield which serves as another magnetic shield and as a thermal shield. In this design, the damper requires thick, strong support to withstand the large crushing loads encountered during a terminal fault. Projections for this design range up to 10,000 MVA.

Other examples of probable applications for superconducting power generation are as follows:(33)

- DC motors and generators for civil marine propulsion
- High-torque motors for steel mill drives and other drive mechanisms
- Ground vehicle propulsion and guidance
- DC generators for aluminum smelting
- Auxiliary drives in power stations
- Light weight airborne power source
- Rapid regulation of output fluctuations in power systems.

All of the above applications and many more not cited are expected to be commercially available by 1990. There are many unique advantages to be gained in the use of ac and dc superconducting generators and motors. These systems have a substnatially increased power density, large flux generating ability, higher terminal voltages, and improved system stability and efficiency. In addition, the economic terminal voltage will rise by a considerable factor.

<u>Superconducting Power Transmission</u>. The initial application of superconducting power transmission is expected to be the transmission of bulk power from an outlying generator station or overhead line loop to a major urban or suburban substation serving a large urban area. An average rating of 4000 MVA, and length of 20 miles was suggested at either 230 or 345 kV and cable fault ratings of 15,000 to 50,000 MVA.(34) This superconducting cable rating is planned for completion in the years 1980-1985. Progress thus far indicates no major unsolved obstacles. The need for conductor development has been met with an Nb_3Sn tape, which is the configuration used in an ERDA-sponsored program at Brookhaven National Laboratory, which utilizes a helically-wrapped flexible ac cable. Other conductor types and/or multifilament conductors have also been sufficiently developed for this use if the need arises.

The dielectric and thermal insulator for the cable probably looms as the largest problem to successful superconducting cable development. The insulation must possess a number of characteristics, both at room temperature and the operating temperature. The requirements of bending, reeling and pulling define the room temperature moduli,strength, and coefficient of friction. The total contraction and variation in the coefficient of contraction are important characteristics of the insulation and greatly influence the design of the composite cable assembly. The goal for the cable under design is an operating stress of 10 MV/m, an impulse breakdown above 80 MV/m (i.e., for a 69-kV prototype) and a corona inception above 15 MV/m. Several good insulator tapes have been found; in fact, the development of materials for the cable has reached the stage to warrant construction of sample cables by commercial high-voltage cable winders.

Alternatively, there are several advantages to using superconducting cable in the dc mode of operation. Direct current has advantages when very long lines are required (over 400 miles), for connections between points separated by water, and for urban feeders. In all three of these areas a detailed cost analysis is needed to determine if the increased capacity offsets the cost of conversion to ac. Even in an optimistic analysis, the break-even distance is considered to be 30 miles.

The following are specific examples of how superconducting power transmission is expected to be applied by the year 1990.

- 2000-5000 MVA supply to congested areas
- High-power density, low-loss transmission over long distances
- Short-distance dc interties.

A superconducting cable with its associated cryogenic envelope and refrigeration system will have to be economically competitive with SF_6, evaporative cooling, and oil force-cooled cables.

At ratings above 3000 MVA, the superconductive cable will likely be superior, both from a cost and performance viewpoint. A one-half mile cable is being constructed at Brookhaven National Laboratory. This cable will be tied in to existing overhead lines and should be fully operative within 2 years. This significant achievement should spur the advance of commercial utilization well before 1990.

The impact of superconducting transmission prior to 1990 will likely fall in the ac mode, with reductions in the cost of conversion from dc to ac possibly changing this situation.

Controlled Thermonuclear Fusion and Magnetohydrodynamics. The controlled thermonuclear research (CTR) program of the U.S. Energy Research and Development Administration is developing superconductors and superconducting systems needed to confine fusion plasmas. Three magnetic confinement systems are being studied, the tokomak, the magnetic mirror, and the theta-pinch.(35)

In a magnetic confinement system, an ionized gas or plasma consisting of deuterium and tritium must be heated to a high temperature and maintain sufficient density to produce an abundance of fusion reactions. The reaction power must be well in excess of the power required to heat the plasma to have a practical steady-state system.

The tokomak system is a torroidal-shaped series of magnet coils. The torroidal field as well as an applied poloidal and vertical magnetic field confines the plasma away from the vacuum vessel walls and, if this condition can be maintained for a sufficiently long time, the energy output will exceed the energy input. A superconducting magnet is needed here to minimize power losses.

In the other two systems, the magnetic mirror and the theta-pinch, the geometry of the magnet system is different; however, the goal is the same--to produce more output power than required input power in a sustained steady-state reaction. In all cases, large superconducting magnets are envisioned. The development work in this country is proceeding at a rapidly accelerating pace. However, an impact on critical materials is not expected until about the year 2025.

In the thermonuclear fusion reactor several key materials will be required in large quantities. These are stainless steels to confine the tremendous forces exerted by the confinement magnet, the super-con conductor needed to wind magnets that are many meters in diameter, and the liquid helium required to maintain the superconducting state. These materials will be discussed in a later section of this report.

A competing technology for superconducting magnetic plasma confinement is laser fusion. The development of laser fusion is proceeding; however, most authorities believe magnetic confinement will be superior.

Much like the fission reactors currently employed, the fusion reactor will be utilized as a central station power source. As mentioned earlier, the commercial utilization of fusion power is not likely prior to 2025; however, several large devices are to be constructed by 1990 for demonstration and feasibility experiments.[36] Currently, the thrust of this fusion research is centered in two national laboratories (Lawrence Livermore Laboratory, Livermore, California, and Oak Ridge National Laboratory, Oak Ridge, Tennessee), and at Princeton University. The larger devices, utilizing magnets with bore diameters of up to 15 meters (49 feet), will impact the superconductor materials market to some extent.

Similar materials considerations and superconducting coil geometries will be involved in magnetohydrodynamics (MHD). Again, the superconducting magnet serves to confine a plasma. It is estimated that MHD will not have a significant impact on critical materials until after the year 2000.

Superconducting Magnetic-Energy Storage. In a Superconducting Magnetic-Energy Storage (SMES) System, large amounts of electrical energy would be stored in the magnetic field of a large superconductive inductor. Superconducting magnetic-energy storage is an alternative to other energy-storage technologies. The capital cost is likely to be greater than for competing technologies; however, the very high efficiencies (95 percent expected) could make the method very competitive, especially with diminishing supplies and increased cost of fossil fuels.

There are three fundamental applications for superconducting energy storage. These applications are defined as follows:[37]

> System Stability. Typically 10^4-10^5 MJ storage capacity, 10 to 600 s discharge time. Although this is not usually thought of as being in the realm of energy storage, it is in fact a form of short-term energy storage in the same sense as, for example, the kinetic energy stored in rotating machines or the thermal energy stored in steam is utilized to control frequency and to meet short-term variations.
>
> Peak Shaving. Typically 10^4-10^5 MJ storage capacity, with 1 to 12 h discharge time. In recent years gas turbines which have high operating costs and low capital costs have been used to provide power during the relatively short periods of peak demand.

These units have been effective because they are easy to control, may be turned on and off without severe thermal cycle problems, are economical (having capital costs of $100-135/kw), and have short lead times for purchasing. Unfortunately, their efficiency is poor and they require high-quality, expensive distillate fuels.

Load Leveling. 10^7-10^8 MJ storage capacity, 5 to 10 h discharge time. For this power system requirement the energy is stored in a device during the hours of light load, usually at night, and is returned to the system during the daytime hours of heavy load. Such operation allows the base load generating units to be run at a relatively constant level, leading to increased plant efficiency. This type of operating is particularly important for nuclear generation. Typically, pumped hydro has been used for this purpose although older fossil-fired plants and gas turbines also have seen some service in this area.

The first application of this technology is expected to be small units on utility systems for the purposes of peak shaving and system stabilization. For these uses, units of 100 MW capacity will be required. It is anticipated that these units will be operational in the 1980's. Because of the relatively small size of these units, no critical materials situation should arise. However, units have been designed with a capacity of 10,000 MW, which represents an entirely different situation. An envisioned 10,000 MW unit would have a diameter of about 60 to 150 meters (155 to 490 feet). In this situation, the structural members, the conductor, and the liquid helium could cause serious material shortages should systems of this size actually be constructed. Even the most optimistic viewer does not see this happening prior to the year 2050, however.

There are several competing technologies that severely challenge the implemention of superconducting magnetic energy storage; however, the solution of several key problems could change this situation. The competing technologies include

- Pumped-hydro storage
- Thermochemical storage
- Compressed-air storage
- Flywheel energy storage.

Projected Market Penetration to the Year 1990 and Requirements for Critical Materials

The market penetration of all of the areas of superconducting technology will be relatively slow for the rest of this decade and the first half of the 1980's; however, in the years 1985-1990, a significant market impact is expected, especially in the areas of superconducting power generation and superconducting power transmission. This market penetration is expected in both military and industrial centers. There are some basic technology and interaction problems which must be overcome. However, technological problems seem to be rapidly falling by the wayside and if one looks at the progress between 1960 and 1970, one can expect an exponential growth rate in this decade and the years which follow. The interaction problem centers chiefly around the public utilities and major industrial manufacturers willingly cooperating with various government agencies in implementing advanced energy schemes. The Electric Power Research Institute (EPRI) is making good strides in this area of interaction.

Realistically, the following market penetration is expected by 1990:

- Delivery of several superconducting power generators for airborne use
- Successful demonstration at key sites of 600 MVA or greater superconducting machines
- Utilization of dc superconducting motors on certain types of marine craft
- Several demonstrations of superconducting motor propulsion for ground vehicles (i.e., magnetic levitation of trains)
- Several miles of superconducting ac and/or dc transmission cable for urban power from remote site
- Incorporation into many utility companies of superconducting energy storage devices for rapid response system stabilization.

We consider this market impact reasonably conservative. Increased appropriations for development work over the currently budgeted amounts would accelerate the market impact.

The critical materials of primary concern in all of the areas of superconducting technology are helium, pure elemental niobium, superconducting alloys, special nonmagnetic structural steels, and copper. It is very clear that if production and extractive metallurgy procedures remain unchanged, the most critical shortages will occur after the year 2025. However, prior to 1990 some effects of the increased demand will be noticeable and, with that reminder, the next 15 years can be well used to prepare for the decades to follow.

In the following paragraphs each material is addressed with respect to current usage, expected usage between now and 1990 and in the following years, and availability.

Helium. In all superconducting devices the temperature of the device must be maintained between 1.8 and 16-18 K. To accomplish this, liquid helium in large quantities is needed. There is considerable concern as to whether or not helium will be available in sufficient quantity. There is reason to believe that adequate helium will be available until 1990. Beyond that, the cumulative helium demand through the year 2050 has been estimated at as high as 470 Gcf[a] whereas helium reserves from natural gas beyond the period 1990-2000 are estimated as low as 100 Gcf. This latter figure depends on how the federal helium management program is implemented. Generally, people involved in superconducting technology program are in favor of a strict helium conservation policy.

The U.S. Bureau of Mines, the Stanford Research Institute, and the Ford Foundation have made helium demand and availability estimates using several criteria.[38] Their results are broadly summarized as follows:

Year	Estimated Demand	Estimated Availability
1975-2000	34 - 77 Gcf	132 Gcf
2000-2050	180 - 470 Gcf[b]	- (c)

For comparison, the U. S. consumption for 1970 through 1974 totalled about 2.5 Gcf.[39]

In each of the superconducting technologies discussed in this report, some estimate can reasonably be made for projected helium usage. It should be emphasized that helium supply/demand between now and the year 1990 appears to be adequate, but this fact cannot lead us to project an attitude of complacency.

(a) Gas technology terminology is Mcf = 10^3 standard cubic feet, MMcf = 10^6 standard cubic feet, and Gcf = 10^9 standard cubic feet.

(b) Note: Assuming 3.5 percent annual energy growth rate.

(c) No reliable estimate available. Depends on conservation program, natural gas supply, and alternate recovery methods.

In the area of superconducting power generation, a reasonable estimate for total helium inventory prior to 1990 is 1-2 Gcf. After 1990, this should increase substantially. Generally, these machines are operated with closed-cycle refrigerators where the helium loss rate should not exceed 10 percent/yr. However, the actual loss rates are running closer to 100 percent/yr at the present time. This is expected to be improved upon.

For superconducting power transmission, the technology will be economically attractive with cables rated above 2000 MVA. It has been estimated that 10,000 equivalent circuit miles of 2000 MVA cable will be installed by the year 2010. This would represent a helium inventory of 12.5 Gcf with an estimated 1 percent growth rate per year. The 1990 helium inventory will be proportionately less.

In the area of controlled thermonuclear fusion, estimates range from 850 to 8500 GW(e) (10^9 watts) of installed capacity in the year 2025. If the superconducting magnetic confinement method is utilized, and it appears very likely, it has been estimated that up to 100 Gcf (or 5-7 times that) of helium inventory will be required. Again, if the losses are 10 percent/yr, this means that 5-10 Gcf make-up will be required per year. This would appear to be out of the question considering projected helium availability.

Superconductive energy storage is not expected to impact the helium market prior to the years 2030 to 2050. A liberal estimate of cumulative helium usage prior to that time is 1 Gcf.

The DoD benefits in many ways from helium availability. For example, in 1970 the U.S. consumed helium in the following ways, all of which directly relate to DoD activity:(38)

Use	Quantity, MMcf
Pressurizing and purging	237
Controlled atmospheres	68
Research	65
Welding	63
Lifting gas	45
Leak detection	42
Cryogenics	33
Chromatography	14
Heat transfer	9
Synthetic breathing mixtures	4
Other uses	7.

In view of these wide and varied uses of helium and the anticipated increase in demand for superconducting devices, as discussed earlier, it is recommended that the DoD consider a position of strong support for the Federal Helium Conservation Program and also consider potential ways of recovering helium from sources other than natural gas.

Niobium (Columbium). Niobium exists in the earth's crust in the amount of 24 ppm; and the ore reserve in the world is estimated at 17 x 10^9 lbs.[39] The U. S. is the main consumer of niobium, but has insufficient niobium resources and must import entire needs. In 1974 these imports, which are in the forms of concentrates and tin slags, came from Brazil (91 percent), Malaysia (2 percent), Zaire (2 percent), and elsewhere (5 percent).[39] Although world ore reserves are predominantly in underdeveloped nations, the refineries are in the U. S., Europe and Japan.[40]

The largest use of niobium is as an additive to steel to improve its properties. To date, the niobium used for superconducting materials (Nb_3Sn and NbTi) is small compared to the overall use. Assuming that these materials continue to be the favored superconductors, niobium demand will significantly increase when superconductors are more fully developed and utilized. The demand estimate for niobium for superconductors alone ranges as high as 2 to 5 million pounds, total, between between 1975 and 1990. In 1990 alone, the demand might reach 300,000 pounds or more. The 300,000-pound figure corresponds to 15 percent of the estimated total U. S. consumption of niobium in 1974.[39] Thus, this amount is not insignificant.

The price of niobium is currently low, because of the large demand by the electronics industry for tantalum. Niobium is a by-product of tantalum production.[41,42] The ores that are processed for tantalum also contain niobium; thus, most of the processing cost required to obtain niobium is borne by the tantalum as it is recovered. If the demand projections of the electronics industry for tantalum[42] are solidified into actual consumptions, there should be no problem in connection with the availability of columbium at reasonable price -- at least into the 1980's.[43] However, if the projected demand for tantalum doesn't materialize, in order to obtain additional niobium it might be necessary to process an ore* specifically for its niobium value. In this case, the processing costs would be borne by the niobium and the necessary selling price could be very significantly higher than the present price for niobium.[43]

*This would be a different ore than is presently processed for tantalum. Roughly, the relative Cb_2O_5 and Ta_2O_5 contents of the ores would be reversed.

Accordingly, two possible problems can be identified in connection with the future supply of niobium. First, reliance on foreign sources of supply for the concentrate or slag. Second, even if the niobium is available, its price may be very much greater than at present, if the demand for tantalum doesn't follow current projections.

Superconducting Alloys. The estimated production of superconducting alloys in 1975 is roughly 50,000 pounds. Demand is expected to increase significantly with time, reaching over 300,000 pounds in 1990. The cumulative demand for superconducting alloys between 1975 and 1990 may exceed 3 million pounds, and perhaps exceed even 5 million pounds.

As the demand for superconducting systems increases, the question arises as to whether or not sufficient manufacturing capacity will be available to produce the required amounts of Nb_3Sn and NbTi in the form of wire and tape.

No capacity problem is anticipated in the early stages of the manufacture of the superconducting materials Nb_3Sn and NbTi.[41] That is, the major producer indicates that significant excess capacity is said to be available for NbTi or niobium* ingot production and initial fabrication operations.[41] Significant excess capacity is said by the two major producers of superconductor wire to be available for the consolidation, drawing, and annealing operations required to reduce the material to its final size, and for final heat treatment.[44,45] Moreover, these companies indicated that additional equipment can be installed to meet future demand.[44,45] The problem at present appears to be lack of major demand, and a preponderence of small orders.

Nevertheless, it is reasoned that a shortage of production capacity for the manufacture of superconductor wire (or tape) may still occur in the future. The financial ability and willingness of companies to invest in new equipment is governed by a number of factors, which are subject to change with time. One of these factors is the availability of capital which, especially for small companies, can be a problem.

Special Nonmagnetic Structural Steels. Very high forces are generated during the operation of superconducting magnets. Very large magnet supports are required in order to resist these forces and enable the magnet to continue operating.

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*Nb_3Sn is not fabricated. Rather, niobium (e.g., wire) is fabricated into a final form while encased in a matrix, after which tin is diffused into the niobium and forms Nb_3Sn *in situ*. Several processes have been demonstrated.

It appears that these supports will be constructed of special high-strength readily fabricable nonmagnetic steels. These steels will probably contain nickel and chromium, the former being largely imported and the latter being 100 percent imported and currently being stockpiled by the United States.

Quantitative demand projections for these steels in this application are not available.

Copper. Copper as a cladding for superconducting wire and tape may be a very serious problem in the years ahead. With costs high and reserves diminishing, the transition to aluminum as a cladding material may be desirable even though there are certain technological problems associated with that transition. For example, the copper requirement for a "world" fusion power system (10^6 MW(e)) is estimated at about 3.6×10^6 tons The other combined superconducting technologies can reasonably be expected to double or triple that quantity. Since U.S. reserves are estimated at 90×10^6 short tons,(39) the possible effect of the demand of superconductor technology for copper should be examined seriously. Foreign reserves add considerably to the supply situation, but reliance on foreign sources is not always acceptable.

Department of Defense Requirements

The principal military use for superconducting technology is in superconducting motors for large ships.(46) These are the main propulsion drive motors, which drive high-torque propellers. Torque level, not horsepower rating, is the factor on which the choice between superconductive motors and other types of motors is based. Superconducting motors are said to be superior to competitive motors at torque levels of roughly 1 million lb-ft and above.(46)

Among the major benefits to be derived from the utilization of superconducting motors on board ship are excellent maneuverability, including the ability to reverse rapidly, and variable speed reduction without the use of gear boxes.

Current research effort by the Naval Ship Research and Development Center at Annapolis, Maryland, and its subcontractors* has as its objective the demonstration of the technical and economic feasibility of a 40,000 hp, 1 million lb-ft torque superconducting motor for U.S. Navy use.(46) The probability of attainment of this goal is said to be 90 percent. (46)

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* General Electric Company, Schenectady, New York, and Garrett Corporation's AiResearch Manufacturing Company of California, Torrence, California.

Fleet operation of these motors some of which could be as large as 75,000 hp, is not expected before 1985. Use will be limited to new ships; retrofitting of existing ships is not feasible. Each ship is expected to utilize between several hundred pounds and about 1000 pounds of superconducting materials. Assuming an average of 600 pounds per ship, 15 new ships per year, and initial usage in 1986, this application will require about 45,000 pounds of superconducting materials by 1990.

A possible U. N. Navy application for superconductor technology is in homopolar superconducting dc generators for use with high-speed gas-turbine engines.(46) These generators are used to drive the ship's motors; their competition is improved,nonsuperconducting rectified alternators. The U. S. Naval R&D Center at Annapolis, Maryland, is supporting research on the two alternative types of machines at Garrett Corporation's AiResearch Manufacturing Company of California in Torrance, California.(46) Which machine will prove best for this application is not known at present.

The superconducting material that is being used for both the motors and the generators is NbTi alloy wire.(46) The Navy is assessing the use of Nb_3Sn wire, the potential benefits being the ability to work at higher magnetic fields and higher current densities, and the smaller amount of wire required when Nb_3Sn is used instead of NbTi.(46)

The U. S. Army is considering the use of superconducting generators in support of future high-power weaponry.(47) The advantages of a superconducting machine for this application are greater mobility and higher efficiency than competing generator systems with the same output. However, inherent in the use of superconducting generators is the necessity of transporting a refrigeration unit with the generator, and the requirement for a liquid helium supply in the field.

Probably the smallest superconducting generator that would be feasible for Army use would have an output of several megawatts. However, even if these outputs are required by the weapons system, if the duty cycle consists of short "on" times and relatively long "off" times, standard nonsuperconducting generators may still be the best choice. That is, standard generators of lower output might be able to be operated at above capacity for the short "on" times, and allowed to cool during the "off" period.(47)

If superconducting units are used in this application, development would probably be during the 1980's.(47) No projection can be made regarding the number of units that might be used or the requirements for critical materials.

Another possible Army use for superconducting technology is in mobile, modular power-generation capacity, which can be deployed rapidly by air or perhaps even by truck.(47) Such equipment might be used both in combat and in civilian emergencies.

Power requirements for barrier lines might also be supplied by superconducting generators.[47]

The USAF has an ongoing program that represents a step toward the goal of developing a new class of high-power, light-weight generators for airborne applications. A 5 MVA power generator is now under test. This machine has an output voltage of 5000 V and a rotational speed of 12,000 rpm. The total machine weight is less than 1000 lbs.

Progress has been excellent. However, areas like improved conductor design and fabrication reliability, improved rotating seal performance, and the need for advanced structural materials to prolong useful life, require significant additional R&D attention.

Potential Procurement and Development Problem Areas for the Department of Defense

The procurement situation for the Department of Defense with respect to superconducting materials is generally similar to that of industry, since similar properties are required in each case. Thus, the possible procurement problem areas relate to the availability of helium and niobium, production capacity for superconducting alloy wire or tape, the supply of nickel and chromium for use in special nonmagnetic structural steels, and the availability of copper. However, the quantities of these materials required for DoD applications are expected to be much smaller than those projected for industrial applications.

DoD development problem areas that need to be addressed are already being attacked on U. S. Navy, Army, and Air Force programs. The major areas are as follows:

- The need to develop superconducting motors and generators for shipboard use. Research in progress at the U. S. Naval R&D Center at Annapolis, Maryland, and by its contractors is attacking this problem area
- The need to develop improved lightweight, readily transportable refrigerators for use with superconducting generators that support high-power weaponry.[47] The U. S. Army Mobile Equipment Research and Development Center is already developing improved refrigeration units for this possible application
- The need to develop high-power lightweight generators for airborne applications. Such research is now being carried out by the U. S. Air Force.

High-Temperature Gas-Turbine Engines for Automotive Applications

by

Thomas R. Wright

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Technical Description of Technology

The utilization of a gas-turbine engine for automotive applications is not a new concept. It has been successfully employed in powering industrial and heavy vehicular equipment. These "state-of-the-art" turbine engines use a conventional combustion system and nickel-chromium-base superalloys for the high-temperature components. According to McLean,[48] three major problems need to be solved before gas-turbine engines can compete in the high-volume automotive market. These are

(1) High emission of NO_x
(2) Poor fuel economy in city driving
(3) Excessive engine manufacturing costs.

Current conventional gas-turbine engines can meet emission regulations with regard to carbon monoxide and hydrocarbons. However, because the turbine operates at a higher temperature than do conventional piston-type engines, NO_x levels in the exhaust are increased. In order to meet the requirements for NO_x emission, new combustion systems are being developed. Because the turbine engine relies on continuous combustion, and continuous combustion systems offer potential for low emissions, this problem does not raise a serious barrier to the development of vehicular turbines.

The solution to the two remaining problems involves materials. Consider fuel economy. As shown in Figure 11[49] increasing the turbine inlet temperature (TIT) of a gas-turbine engine results in significant decreases in specific fuel consumption (which increases engine efficiency) and specific air consumption (which enables a reduction in size) of an engine. At present, uncooled nickel-chromium-base superalloys are limited to a maximum TIT of $\sim$ 1900 F; blade cooling is not practical for small turbine engines. Because of the temperature limitations of superalloys, ceramics offer the only presently identified alternative for achieving these required elevated temperatures.

Excessive engine manufacturing costs present perhaps the biggest obstacle in applying the gas turbine to high-volume production vehicles. To be cost competitive, turbine components must be made from inexpensive raw materials by an inexpensive fabrication process. The potential for cost reduction in the raw materials using ceramics is shown in Figure 12.[50] Total superalloy raw materials cost is estimated to be up to $6.00/lb. The estimated raw materials cost for silicon nitride (silicon and nitrogen) is $0.71/lb.[51] Additional effort is required to develop inexpensive fabrication processes for ceramic engine components, however.

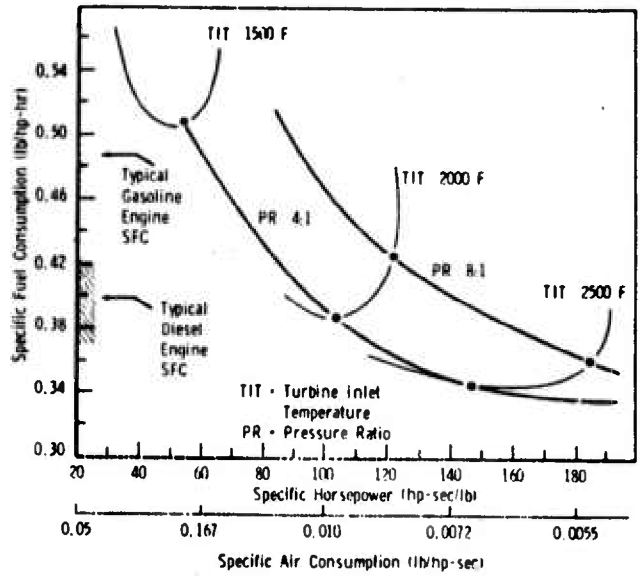

FIGURE 11. SPECIFIC AIR AND FUEL CONSUMPTION RELATIONSHIP FOR A REGENERATIVE GAS-TURBINE ENGINE

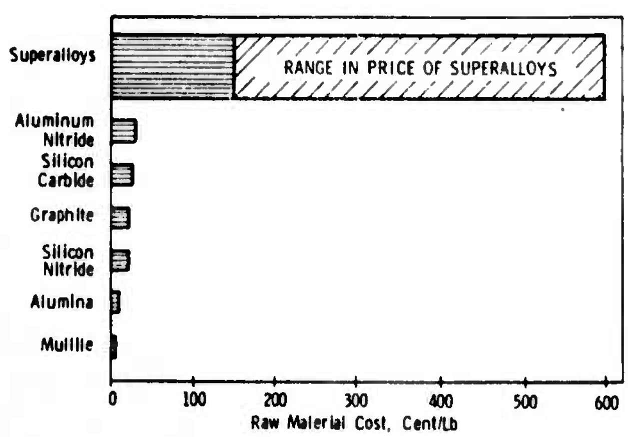

FIGURE 12. RELATIVE RAW MATERIALS COST

Along with raw materials cost, raw materials availability is considered to be an important advantage of a ceramic turbine. Table 6[52] illustrates the present and potential availability of the critical alloying elements in the superalloys used in gas-turbine engines. It will be noted that imports supplied practically all of the 1970 U.S. domestic demand. A similar situation existed in 1974, although the percentage figures were somewhat different.[53] The locations of most of the current foreign sources are not favorable. The raw materials for the appropriate ceramics, on the other hand, are available in readily abundant sources in the U.S.

TABLE 6. PRESENT AND POTENTIAL AVAILABILITY OF CRITICAL METALS FOR HIGH-TEMPERATURE TURBINE ALLOYS

METAL	CURRENT SUPPLY (U.S. IMPORTS AS A PERCENT OF DOMESTIC USE 1970)	ULTIMATE SUPPLY (U.S. RESERVES AND RESOURCES)	CURRENT SOURCES
CHROMIUM	100	INSIGNIFICANT	USSR, SOUTH AFRICA, TURKEY
COLUMBIUM	100	DATA UNAVAILABLE	BRAZIL, NIGERIA, MALAGASY
NICKEL	91	LARGE, ASSUMING SIGNIFICANTLY INCREASED WORLD PRICE OR NEW EXTRACTION TECHNOLOGY	CANADA, NORWAY
COBALT	91	DATA UNAVAILABLE	ZAIRE, BENELUX COUNTRIES

Source of Data: Final Report of the National Commission on Materials Policy, June 1973, U.S. Government Printing Office

The basic parts of an automotive gas-turbine engine are the compressor, the regenerators, the combustion chamber, and the turbine. In the current automotive turbine design, air, induced through a radial compressor, is compressed and ducted through one side of each of two regenerators. The hot compressed air is supplied to the combustion chamber where fuel is added and combustion occurs. The hot gas from the combustion chamber is directed into turbine stages by a nose cone.

The turbine stages comprise two turbine stators, each having stationary airfoil blades to direct the gas onto each corresponding turbine rotor. In passing through the turbine, the gas expands and generates energy to both drive the compressor and to supply useful output power. The expanded turbine exhaust gas is directed through the hot side of each of the two regenerators which, to conserve fuel consumption, transfer much of the exhaust heat back into the compressed air.

At the present time, ceramic materials are being considered as hot-flow path components for the above engine operation. The components include

- First-stage turbine stator
- First-stage turbine rotor
- Second-stage turbine stator
- Second-stage turbine rotor
- Turbine inlet nose cone
- Combustion chamber
- Regenerators.

Currently, with the exception of the regenerators, ceramics based on silicon, nitrogen, and carbon are being considered for use as these components in the vehicular gas turbine. The major development effort in the U.S. in this area is the ARPA/Ford study which has the aim of the demonstration of ceramic hot-flow path components operating uncooled for 200 hours of typical duty-cycle operation at 2500 F TIT.[51] This program is now approximately at the midpoint.

In order to provide a plan for the orderly transition from the ARPA/Ford 200-hour technology demonstration to a complete prototype engine demonstration, the ERDA Advanced Automotive Power System Division has initiated a follow-on program with an eventual goal of a 100-125 hp engine to operate at 2300-2500 F (TIT) for 3000-4000 hours. A milestone chart of the ARPA/Ford and ERDA/AAPS total program is shown in Figure 13.[54] Later information indicates that the specific aim of ERDA/AAPS is to demonstrate the engine for automotive use by 1984.[55] The required research includes component development and the building of about 12 engines.[55] It is possible that a pilot plant for the production of automotive gas-turbine engines using ceramic hot-path parts will be built by 1984.[55]

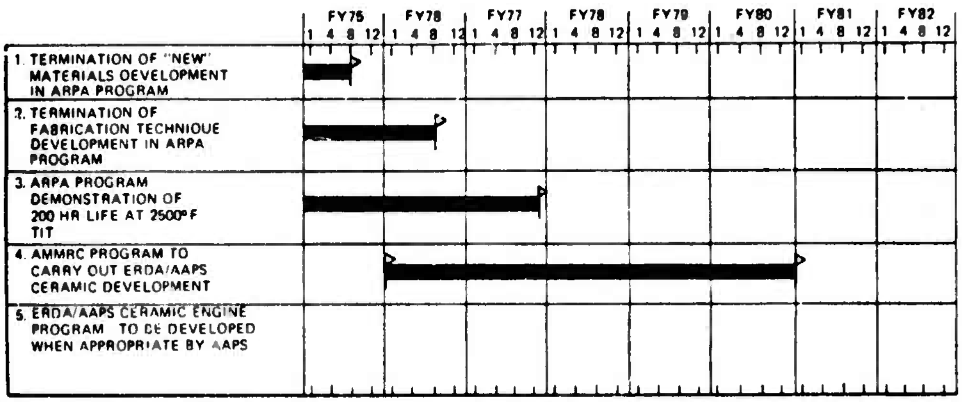

FIGURE 13. PROPOSED MILESTONE CHART ERDA/AAPS CERAMIC MATERIALS AND COMPONENT DEVELOPMENT PROGRAM [54]

Silicon nitride (Si_3N_4) and silicon carbide (SiC) are receiving prime consideration as materials for the ceramic turbine components. Other materials which show promise, and which may receive increased consideration in the future, are aluminum nitride (AlN) and SiAlON (Si_3N_4-Al_2O_3 solid solution). Figure 14[54] summarizes the individual component status on the basis of materials and their possible fabrication technique. In this figure M-A-S and L-A-S refer to magnesium aluminum silicate and lithium aluminum silicate, respectively.

CERAMIC COMPONENT	MAX. PART TEMP. °F	MATERIAL I Si_3N_4	II SiC	III SIALON	IV M-A-S	V L-A-S	PROCESS COLD PRESSING	SLIP CASTING	INJ. MOLDING	"REFEL" TYPE	HOT PRESSING	CHEM. VAP. DEP.	EXTRUSION	SINTERING	PAPER WRAPPING	GLASS FORMING
1ST STAGE STATOR	2400	✓	✓	✓				Ib IIb	Ib IIb	IIb				IIb IIIc		
2ND STAGE STATOR	2100	✓	✓	✓				Ib IIb	Ib IIb	IIb				IIb IIIc		
1ST STAGE ROTOR	2300	✓	✓	✓				Ib IIb	Ib*		Ib† d†	IIc		IIb IIIc		
2ND STAGE ROTOR	2000	✓	✓	✓				Ib IIb	Ib*		Ib† d†	IIc		IIb IIIc		
1ST STAGE SHROUD	2300	✓	✓	✓			Ib	Ib IIb		IIb	Ib			IIb IIIb		
2ND STAGE SHROUD	2000	✓	✓	✓			Ib	Ib IIb		IIb	Ib			IIb IIIb		
INLET NOSE CONE	2500	✓	✓	✓					Ib IIb					IIb IIIc		
COMBUSTOR**	2500		✓	✓						$\boxed{\text{IIa}}$			IIb	IIb IIIc		
REGENERATORS	1800	✓		✓	✓	✓							IVb Vb		$\boxed{\text{Ib IIIc Va}}$	IVb Vb

a = Currently in Hardware Demonstration at Temp; Highlighted by ▭
b = 1-3 Years Hence
c = 3-5 Years Hence
d = Technically Feasible but Economically Unattractive

*Hub only for Multi-Density
†Monolithic
‡Blades only for Multi-Density
**A Low Emission Combustor Would Require 2800 F Capability

Status as of 15 July 1974

FIGURE 14. MATERIALS AND PROCESSES FOR UNCOOLED CERAMIC COMPONENTS FOR A CERAMIC ENGINE AT 2500 F TIT(54)

According to a recent assessment by the U.S. Army Materials and Mechanics Research Center (AMMRC) in Watertown, Massachusetts,(54) there is greater than 50 percent possibility that the ARPA/Ford program goals will be achieved. It is virtually certain that the stationary components (cones, shrouds, combustor, and inlet nose cone) will have demonstrated 200 hours of duty cycle at 2000 F or greater. Already the nose cone, shroud, and regenerators have exceeded 200 hours at 1930 F while the stators have been operated for 50-100 hours at the same temperature.

At the present time, the major difficulties or shortcomings to the program appear to lie in the rotor component. The current approach followed by Ford is the duo-density rotor consisting of a slip-cast or injection-molded reaction sintered silicon nitride (RSSN) blade ring (for high creep resistance) bonded to a hot-pressed silicon nitride (HPSN) hub (for high strength).

Reaction sintering takes advantage of conventional powder metal forming techniques such as slip casting or injection molding to prepare a silicon powder preform. The preform can be converted to the nitride by sintering it at an elevated temperature in a nitrogen-containing gaseous atmosphere. Reaction sintered structures are naturally creep

resistant due to the absence of a grain boundary phase; however, because RSSN is less than theoretically dense, the strength is low. The process has the advantage of preparing complex shapes to nearly exact dimensions. Hot pressing involves the densification under pressure of silicon nitride powder containing a specific amount of a densification aid. Magnesium oxide is the most commonly used additive.

Ford has cold spin tested duo-density rotors to 55,700 rpm. Only a profiled rotor hub has attained a characteristic speed of 115,000 rpm. It is unknown whether or not there has been a successful demonstration of a hot-spin test on complete rotor components.

The major problems experienced with the rotors developed on the ARPA/Ford study are a lack of realistic strength in the RSSN blade ring and the HPSN hub. There are several potential approaches to solving these problems; however, from a practical point of view, the two most promising appear to be

(1) Development of a strong, easily fabricated, blade ring for the duo-density approach

(2) Development of a single piece, monolithic, rotor assembly.

The first approach, duo-density, requires an improved high-strength rotor blade ring that exhibits strengths comparable to that of HPSN yet retains the creep resistance of RSSN. Because of the complexity of shape, it would be ideal if such structures could be fabricated by an approach such as cold forming and sintering.

While this is not possible currently with pure silicon nitride, such an approach may indeed be feasible with the SiAlONs. It has been reported that such materials can be sintered to high density; however, considerable development is needed to bring the material to the current status of Si_3N_4.

It is believed that properly prepared SiAlONs can have improved properties over current silicon nitride materials. Using high-purity processing, Battelle-Columbus investigators[56] developed a grain-boundary-engineered SiAlON by hot pressing, which exhibited a creep resistance two orders of magnitude greater than that of currently commercially available grades of HPSN at 2550 F under a stress of 10,000 psi.[57] These investigators have also recently prepared comparable density structures by a modified sintering approach.

The second approach, the development of a single-piece, monolithic rotor assembly, could be employed to circumvent the bond failure of the duo-density rotor approach. Two concepts might be utilized to prepare a one-piece complete rotor. One involves the use of SiAlON materials, optimally developed. The other concept involves the use of high-strength, high-density, reaction-sintered silicon nitride, which also requires development effort.

One technique for obtaining high density, and subsequently high strength, in RSSN is to slip cast the material to a high green density engineered to yield a high ($\geq$ 95 percent) density upon conversion to the nitride. This is not possible by 1-atm nitridation but must be performed under high pressures to insure an adequate supply of nitrogen to the interior of the part.

Currently, material can be prepared that exhibits densities of ~ 92 percent of theoretical or conversion to the nitride. Cursory strength measurements have indicated strengths of approximately 50,000 psi.[58] With structure refinements to eliminate strength-limiting flows apparent in the material, flexure strengths of 60-70,000 psi should be possible at this density level. Additional refinements in particle size, particle size distribution, nitriding schedule, and other variables, have the potential for increasing the strength levels to 100,000 psi. If this type of strength level can be achieved, the production of a one-piece RSSN rotor will be a reality.

It is believed that these types of rotor improvements are necessary to fit the technology needs of the 1990 time frame or even the 1981 ERDA/AAPS goals. It is believed that, with a reasonable research effort, the high-density, high-strength RSSN material could be developed by 1977. The sintered SiAlON's would require a 5-year period to reach the current engineering status of HPSN.

Other competing technologies include the development of a sintered SiC rotor which could mesh nicely into the current design. Silicon nitride has several advantages over the carbide; however, if the nitride cannot be proven as a rotor material on the current ARPA/Ford program, design conditions may be reduced or relaxed to allow use of the carbide.

Industrial Applications for the Technology

The primary industrial application for the small gas turbine engine will be in the automobile field. Deployment of the turbine in passenger vehicales may well provide a large market by 1990. Other related areas may be in the area of mass transit. The small turbine may be an ideal system for mini- or shuttle-bus transportation within urban areas.

It is believed that by 1990, technological advances in turbine technology, brought about by the effort on the automotive turbine, could also provide vast increased utilization in the area of heavy vehicles i.e., trucks and buses. Also, the turbine may find utilization as a marine engine and as such could be utilized in pleasure craft or water transportation.

Technological developments that increase the efficiency of gas turbine engines for the above applications will also provide guidance and direction for other important applications such as stationary power turbines. This concept is currently under development by Westinghouse Electric Corporation as a subcontract on the ARPA/Ford study. The aircraft industry would also benefit from the technology being developed. Low-cost, high-performance ceramic turbines will find application in remotely piloted vehicles, drones, and missiles. In order to be fully utilized in these applications, the materials will require eventual upgrading to withstand TIT's of 3000 F, considerably above the current state of the art. This is not impossible, but will require continual material development and upgrading to meet the higher design requirements. Again Si_3N_4- and SiC-base ceramics will probably be utilized but not without a considerable material development effort.

Because of the obvious advantages of the gas-turbine engine over current piston engine vehicles (multifuel capability, efficiency potential, lower emissions, etc), it is particularly important from the viewpoints of economics and fuel economy that the concept be developed and into production by 1990. In theory, turbines can run on alcohol, which can be made from garbage.

It is important to note, however, that there are technologies that compete with the gas-turbine engine. For example, considerable effort is being expended toward development of the Stirling engine. This engine offers many of the same potential advantages as the turbine. For instance, the Stirling can also operate at a high efficiency and also has multifuel capability. Exhause emissions are low. Moreover, test results to date indicate that current engine designs can meet the 1988 California Vehicle Code with regard to noise. ERDA/AAPS has also recently initiated an automotive Stirling engine program, which is intended to have production models available by the mid-1980's.

In addition to the U.S. efforts in turbine engines, various foreign efforts are under way in the U.K., Japan, and Germany. Among the overseas companies involved are British Leyland, Daimler-Benz, Volkswagon, MTU, Toyota, Honda, and Nisson Motors.

It has been reported that Toyota has successfully cold-spun rotors to 77,000 rpm.(59) This is nearly a 40 percent improvement over the best U.S. cold-spin tests to date. Toyota uses a rotor comprised of hot-pressed blades mounted with an unknown padding material to an alloy hub.

If U.S. technology cannot solve the current problems before the 1990 timeframe, and if the foreign producers market a ceramic turbine vehicle first, there could be severe economic repercussions. Fully, one in six people in the U.S. is engaged in activities associated with the automotive field. Further inroads by the foreign imports would be disastrous for this large segment of industry.

Projected Market Penetration by 1990 and Requirements for Critical Materials

Market Penetration. Market penetration by 1990 is quite difficult to forecast. Engine development will follow materials development and therefore progress accordingly. In addition, emphasis on development in the next 15 years will also be governed by the emphasis of the nation. As an example, Figure 15[60] illustrates the cyclic trends during the past 4-year period with regard to emphasis, the "mood-of-the-people", and the world economic picture. Market penetration will also depend on the extent to which Stirling engines capture a share of the market.

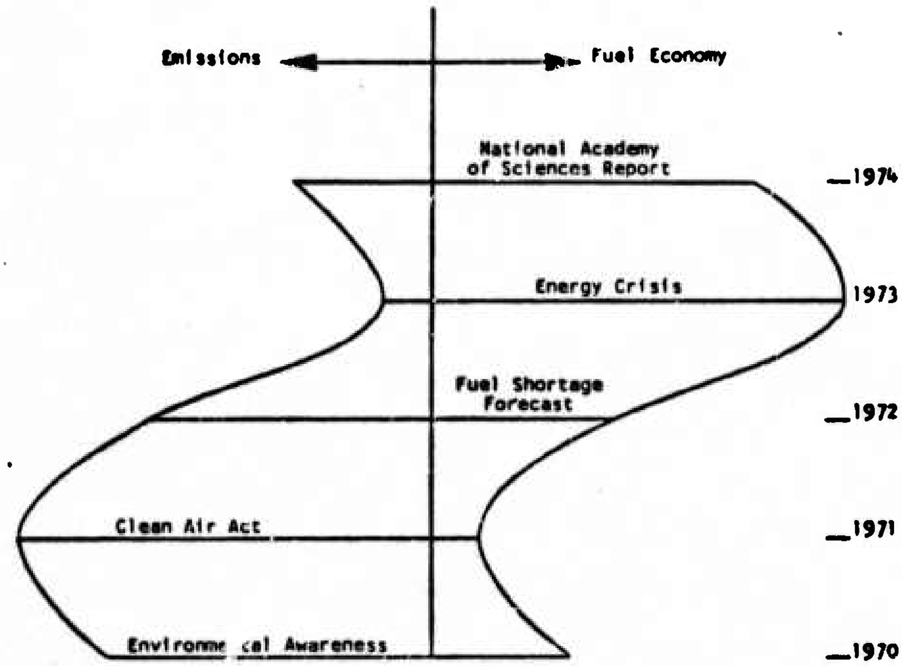

FIGURE 15. GAS TURBINE PROGRAM RELATIVE EMPHASIS BETWEEN EMISSIONS AND FUEL ECONOMY

It is believed that future trends will probably be dictated or influenced by fuel economy/supply. This being the case, and if the ERDA/AAPS program is successful in developing a production demonstration engine, automotive manufactures should be in a position to begin marketing turbine-powered vehicles before 1990.

At this stage of development, projections of market penetration are particularly risky. However, it is roughly estimated that the automotive market penetration may reach 10 percent by 1990. Penetration should grow rapidly with increasing public acceptance.

Types of Materials and Areas of Application. Silicon nitride and silicon carbide are the two critical materials of concern in automotive gas-turbine engines. They are the most promising materials for the construction of the hottest parts of high-turbine-inlet temperature gas turbines for this application. It is expected that these materials, or modifications thereof, will remain the prime candidates for use in 1990. Other materials which may begin to find utilization are AlN and the SiAlONs. Material candidates for the rotor assembly over the next 5-year period (through 1980) are shown in Table 7.[52]

TABLE 7. CANDIDATE ROTOR MATERIALS[52]

Component	Present Materials	Additional Materials 2 Years From Now	Additional Materials 3 to 5 Years From Now
Blades	RSSN, Sintered SiC, HPSN	AlN	SiAlON, chemically vapor deposited SiC
Disks (hub)	HPSN	Sintered Si_3N_4, Sintered SiC	SiAlON
Monolithic Rotor	Duo-Density Si_3N_4	HPSN, Sintered Si_3N_4, Sintered SiC	SiAlON, SiC, or Si_3N_4

It is believed that, in addition to the materials listed, SiAlONs could be utilized as turbine disks within 1 to 2 years from the present. Also, it is strongly believed that a one-piece rotor of high-density RSSN could be produced within a 2-year period. Of course, this can occur only with the continued disposition of development funds.

Projected Quantity Requirements. The current design of the automobile gas-turbine engine on the ARPA/Ford program requires approximately 10 pounds of silicon nitride per car.[61] If one were to assume that 15 million automobiles are to be built in 1990 and that 10 percent of them are powered by gas-turbine engines, the requirement for silicon nitride for this application in 1990 would be 15 million pounds (based on the present design). The ERDA/AAPS engine will be of a lower horsepower and will probably be smaller in size. This may well require less material than the present Ford design.

It is important to note that ceramics, especially Si_3N_4 and SiC, are candidates for use in advanced diesel engines and in Stirling engines.[55,62] Thus, the market for these materials in automotive applications is not dependent entirely on gas-turbine engines.

Materials Production Capacity. This area may be discussed with regard to industrial capability in two major areas:

- Production of Materials
- Production of Components.

Materials Production. According to the AMMRC assessment,[54] at present the supply of ceramic materials is insufficient. Specifically, AMMRC found that at present there is insufficient materials production and/or fabrication capacity in the area of turbine ceramics to support a major engine demonstration program. Nevertheless several potential future quantity suppliers of materials are active in the field and in some cases have assumed a pseudo-leadership role. The fact that these manufacturers have established this relationship and are operating limited production facilities should facilitate scale-up to full production requirements in the future. However, even these companies find it very difficult to justify investing in a product that has only a small, uncertain market at present and an indefinite market within the next few years.[62] Moreover, technological changes and advances occurring so rapidly that many industrial suppliers are reluctant to make a capital investment, or are unable to produce a firm product line, until the market and technology stabilizes.

Product standardization, quality uniformity, and property improvement remain as problems.

A listing of suppliers of silicon metal, silicon nitride, and silicon carbide (both power and consolidated billets) is given in Table 8[54] as per the AMMRC assessment. Because they are not considered engineering materials at present, SiAlONs were not included.

Component Production. With regard to component supply, the current commercial production capability is not sufficient for a large-scale demonstration program.[54] In addition to the market being demand sensitive, the components to be produced are fabrication-process sensitive Again, advances in fabrication technology are proceeding at such a rate (on a laboratory scale) that current producers of components are probably reluctant to invest capital in what soon might become an outmoded procedure or process. Despite these laboratory advances, significant research is required to develop production-scale manufacturing technology to enable the fabrication of complex parts with the desired properties throughout their cross sections.[62]

TABLE 8. SOURCES OF SUPPLY - SILICON, SILICON NITRIDE, AND SILICON CARBIDE [54]

Supplier	Si Powder a	Si Powder b	Si_3N_4 Powder	SiC Powder	Reaction Bonded Si_3N_4	Hot-Pressed Si_3N_4	Hot-Pressed SiC	Remarks
Apacha Chemicals Inc., P.O. Box 17 Rockford, Il 61105	-	-	High β	-	-	-	-	
Atomergic Chemicals Co., (Div. of Gallard-Schlessinger Chemical Corp.), 584 Mineola Ave. Carla Place, L.I., NY	X	X	High β	-	-	-	-	
Carborundum Co. Niagara Falls, NY 14302	-	-	-	X	-	-	-	Also supplies dense SiC
Cerac Inc., Box 597 Butlar, Wis. 53007	X	X	High β	-	-	X	-	
Caradyne Inc., 8948 Fulbright Ave. Chatsworth, CA 91311	-	-	-	-	-	X	-	
DAR-LAC-OID Chemical Corp. Elizabeth, NJ	-	X	-	-	-	-	-	
E.I. duPont deNemours & Co. Pigments Dept., Experimental Station, Wilmington, DE 19898	-	-	High α, amorphous	-	-	-	-	Powder process under development not available commercially
Electronic Space Products Los Angeles, CA	X	X	-	-	-	-	-	
Fiber Matarials Inc., Biddeford Industrial Park, Biddaford, ME	-	-	High α	-	-	X	X	Powdar process under davelopment
GTE Sylvania, Towanda, PA	-	-	High α, amorphous	-	-	-	-	
Kawecki Berylco Industries Corp. 220 East 42nd St., New York, NY	-	-	-	-	-	-	-	
Matarials Research Corp. Orangaburg, NY 10962	-	-	High β	-	-	-	-	
Norton Co., One New Bond St. Worcester, MA 01606	-	-	Make for own use	X	X	X	X	Also supplies dense SiC (non-hot pressed)
Plessy/Frenchtown, Eight & Harrisons Sts., Frenchtown, NJ	-	-	High purity, high α	-	-	-	-	
PPG Industries, Pittsburgh, PA	-	-	-	X	-	-	-	Experimental material
Rasaarch Organic/Inorganic Chemical Corp., 11686 Sheldon St. Sun Valley, CA 91352	X	X	X	-	-	-	-	
Union Carbide Corp., Ferro Alloys Div., Mining & Metals Div. P.O. Box 72, Marietta, OH 45750	X	-	-	-	-	-	-	
Vantron Corp., Alfa Products	X	X	X	-	-	-	-	
Mulco, Salt Lake City, UT	-	-	α, oxynitride	X	-	-	-	Powdar made from rica hulls
Advanced Matarials Ltd. Gatashead, Co. Durham, NE 11 OUF, England	-	-	High α	-	-	-	-	
Dunstan & Wragg, Ltd., England	X	-	-	-	-	-	-	
Koch-Light Laboratories, Ltd. Colnbrock, Bucks., England	X	-	-	-	-	-	-	
Joseph Lucas Group Research Centre Solihull, Warwickshire, England	-	-	Make for own usa	-	-	X	-	
Murex Ltd., England	X	-	-	-	-	-	-	
Pechinay, 23 Rue Balzoe Paris 83, France	-	-	-	-	-	-	-	
Upsil Ltd, England	X	-	-	-	-	-	-	
Rosanthal/AME Selb, W. Germany	-	-	-	-	X	-	-	
Annawerk, Rodental, W. Germany	-	-	-	-	X	X	-	
U.K. AEA, Springfield, England	-	-	-	-	-	-	-	Rafal SiC

a = 99% pure
b = 99.99% pure

The component supply situation is summarized below.[54]

Components	Supply
Rotors	Unavailable
Stators	Marginally available
Combustors	Available on order
Nose Cones, Shrouds, etc	Not a major problem

From this tabulation, it may be reasoned that availability (supply) increases as the component design becomes fixed and as the state-of-the-art material properties begin to meet component requirements.

Basis for Criticality Judgment. Certainly there is no intrinsic scarcity of silicon, nitrogen, or carbon--the basic components of silicon nitride and silicon carbide. However, at present there is very little commercial manufacturing capability for the economical production of these materials with the proper characteristics for this application. Accordingly, the basis for the criticality judgment in regard to silicon nitride and silicon carbide for automotive applications is the possible lack of component manufacturing capacity in 1990 to meet a possibly projected 15 million pound demand for automobiles alone.*

No exact figure is available for the present Si_3N_4 and SiC component-manufacturing capacity in the U.S. Nevertheless, it is very small, as attested to by the conclusions of AMMRC on the present component supply situation, shown in the tabulation in the preceding secion. The company that is probably the major manufacturer of these components has indicated that it is in a position to expand its manufacturing capacity for these components as it sees the market volume increase and can demonstrate profitability for the product line.[62] Also, it is possible that automobile manufacturers would be interested in establishing manufacturing capacity.

Nevertheless, a very large increase in production volume would be required in order to satisfy a possible market demand of 15 million pounds of these components in 1990. Moreover, significant improvements in manufacturing technology will be required in order to decrease manufacturing cost and increase properties, before the new production capacity can be installed. Because of the large amount of capital required both for the development efforts and the new production capacity, it is reasoned that a lack of availability of production capacity may make ceramic materials in the form of gas-turbine-engine components critical materials by the year 1990.

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* This statement relates primarily to silicon nitride, which is currently the prime candidate for these applications, although silicon carbide is being investigated as an alternate material.

Department of Defense Requirements

The U.S. Army, Air Force, and Navy visualize automotive applications for high-temperature gas-turbine engines using ceramics and are carrying out research to pursue these interests. A summary of the anticipated benefits for these types of engines over current engines is as follows:[62]

- Lower specific fuel consumption
- Higher power density (per unit weight and per unit volume)
- Greater range and/or payload
- Increased reliability and decreased maintenance (because of enhanced over-temperature capability and, in some cases, because of enhanced resistance to erosion-corrosion)
- Multifuel capability, which has a logistic benefit and also the strategic benefit of reduced dependence on foreign fuels
- Can be designed to offer high acceleration, i.e., agility
- Reduction in requirements for strategic materials (nickel, chromium, cobalt, and columbium)

A triservice use for gas-turbine engines utilizing ceramics is limited-life engines for drone aircraft, remotely piloted vehicles (RPVs), and air-breathing missiles. The advantages forseen with respect to competitive engines in this application are[55,63]

- Smaller size, because of increased thrust per pound of air flow
- Potential for lower cost
- Increased range and/or payload
- Lower radar cross section.

To date, ceramic stationary hot-path components have been demonstrated with 50-hour life. Inasmuch as the entire service life in some applications may be less than 1 hour, it appears that current ceramic-engine-part technology may be essentially sufficient for these applications.[55,63] However, it is understood that the eventual goal is a TIT of 3000 F in certain of these applications.

The U.S. Army Mobile Equipment Research and Development Center at Fort Belvoir, Virginia, is developing a 10-kw gas-turbine-driven generator set which utilizes a ceramic first-stage nozzle guide vane.[55,63]

The advantage of ceramics in this application is increased erosion resistance. Erosion resistance is important when this set is used as an auxiliary power unit on a helicopter, under combat conditions. The erosion resistance of the ceramic vane has been shown to exceed that of the standard vanes made of the N-155 alloy.(55)

The U.S. Army is also investigating gas-turbine engines that utilize ceramics, for the propulsion of combat vehicles such as tanks and trucks.(64) Research by the U.S. Army Tank Automotive Command in Warren, Michigan, is directed towards an engine with a TIT of 2500 F in the 1980 to 1985 time frame. The potential advantages in such applications would be agility (i.e., rapid acceleration) and potentially a higher power density (phrased in hp/unit weight or hp/unit volume). The disadvantages of a gas-turbine engine here would be a high-polar inertia (which could by keeping a high idle speed in the gasifier), high fuel consumption at low load and at idle, and high production cost. The primary competition in this application is the diesel engine, rearch on which is also being funded by the same organization.(64) If tanks powered by gas-turbine engines containing ceramic parts go into production in the late 1980's and after, the requirement for ceramics might be roughly 5,000 to 20,000 pounds per year. This is based on a "few hundred" tanks per year and somewhere between 10 and 100 pounds of ceramic per tank.(64)

The U.S. Army Air Mobility Research and Development Laboratory at Fort Eustis, Virginia, is planning to propose a feasibility study of the use of gas-turbine engines containing ceramics as the primary power unit in helicopters.(63) However, much improvement of ceramics would be required before they would be used in such a manned application. Among the areas in which improvements may be required are ballistic impact, short-time strength, creep strength, resistance to thermal shock, and reproducibility.(63)

The U.S. Naval Air Propulsion Test Center in Trenton, New Jersey, is investigating ceramic roller bearings for engine use. Increased contact-fatigue life and the ability to withstand higher rotational speeds without damage from centrifugal ball loads, against steel, are anticipated.(55)

Research sponsored by the U.S. Air Force Aero-Propulsion Laboratory at Wright-Patterson Air Force Base, Ohio,* is centered around the use of Si_3N_4 for turbine vane endwalls (platforms).(65) The replacement of cooled superalloys by ceramics in this application is expected to reduce the total turbine cooling airflow requirement by 1.3 to 1.5 percent, leading to an increase of about 0.4 to 0.5 percent

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* Contractor: Pratt and Whitney Aircraft Division, United Technologies Corporation, East Hartford, Connecticut.

in turbine efficiency and 0.5 to 1.0 percent in thrust specific fuel consumption.[65] An increase of 1.3 to 1.5 percent in thrust-to-weight ratio is anticipated.[65] However, leakage through the clearances (between the endwalls and the supports) that are required in order to ensure that binding does not occur may at least partially offset these anticipated benefits.[65]

Potential Procurement and Development Problem Areas for the Department of Defense

The primary procurement problem area that might arise for the Department of Defense in regard to this technology is a possible inability to obtain complex ceramic gas-turbine-engine components in the desired configuration, with the required properties, and at what is deemed to be reasonable cost. As noted in a previous section, economical production-scale manufacturing processes for component shapes need to be developed before these parts will be available. Moreover, if ceramics are used in a high-volume application such as automobiles, the quantity requirements of the Department of Defense will be only a small fraction of the industrial market. In addition, only a few companies may be technically qualified to make the components. These situations might, in themselves, lead to procurement problems for the Department of Defense.

A number of potential development problem areas for the Department of Defense are envisioned. Some of these are common to both military and industrial users, as follows:

- The development of economical production-scale manufacturing procedures to enable the fabrication of complex ceramic components with the desired properties throughout their cross section
- The development of ceramics that possess the improved properties required in both rotating and nonrotating parts of gas-turbine engines
- The development of design criteria and procedures for utilizing ceramics in the specific applications visualized
- The development of approaches to solving the metal/ceramic interface problem.

Development problems relating to the specific Department of Defense applications that are envisioned at present are already being addressed by the U.S. Army, Navy, and Air Force, as indicated in the preceding section.

Fuel Cells

by

John E. Clifford and Eric W. Brooman

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Technical Description of the Technology

Fuel-cell systems have been in existence for many years; the peak in research and development efforts probably occurred about a decade ago. Since that time, because of the de-emphasizing of the space programs, and also some disenchantment with fuel cells because they appeared not to be living up to the promise of being an inexpensive method of electricity generation, interest waned. Now, with the uncertainty of fossil fuel availability, the increase in price of fossil-fuel feedstocks for bulk electricity production, and the increasing costs of electrical power transmission and distribution, interest in developing fuel cells for industrial, commercial, and residential applications has been renewed. In this sense the development of fuel cells is an emerging technology. If the problems identified earlier of high capital cost and short life can be resolved, then considerable market penetration could result in the United States within the 1990 time frame, as discussed in a subsequent section. There are favorable trends in reducing cost and extending service life of fuel cells, and in the utilization of alternate fuels, primarily hydrogen from various feedstocks. With the inherent flexibility and high efficiency of fuel-cell systems, it is felt that there is a basis for some optimism concerning the future commercialization of fuel-cell technology.

Typical fuel-cell systems*, embracing various combinations of the possible design variables, are listed chronologically in Table 9, and reflect the aforementioned cyclic interest that fuel cells have experienced. For the most part, the systems listed were prototype hardware demonstrations of the existing technology, designed to meet specific requirements in transportation, space, residential, and military applications. The current trend appears to be a focusing upon the commercial, residential, and military applications. The one major exception to this trend is the joint Exxon-Alsthom multimillion-dollar program initiated in 1920 and directed toward vehicular applications.

A fuel-cell system consists of three subsystems: (1) the fuel-processing subsystem, (2) the fuel-cell assembly itself, wherein electric power is generated, and (3) the power-conditioning subsystem. The latter is necessary to convert the relatively low-voltage dc power generated into

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*Based upon data in most part taken from Reference 66.

TABLE 9. TYPICAL FUEL-CELL SYSTEMS[a]

Corporation	Item	Power	System	Date
Allis-Chalmers	Tractor	15 KW	H_2/KOH/Air	1959
General Electric	Manpack, military	200 W	H_2/IEM/Air	1961
Allis-Chalmers	Golf cart	3 KW	N_2H_4/KOH/O_2	1962
M. W. Kellogg	Power source	16 KW	Na-Hg/KOH/Air	1963
General Electric	Gemini, power source	1 KW	H_2/IEM/O_2	1964
Univ. Bonn	Battery light buoy	30 W	MeOH/KOH/Air	1964
Westinghouse	Cell stacks	100 W	CO-H_2/SE[b]/Air	1965
Union Carbide	Fieldpower, military	300 W	N_2H_4/KOH/Air	1966
Alsthom	Cell stack	2 KW	N_2H_4/KOH/H_2O_2	1966
Pratt & Whitney	Apollo, power source	1.5 KW	H_2/KOH/O_2	1966
Esso R&E Co.	Prototype	100 W	MeOH/H_2SO_4/Air	1966
Allis-Chalmers	Field power, military	5 KW	H_2[c]/KOH/Air	1966
Union Carbide	Minibus	32 KW	H_2/KOH/O_2	1966
Monsanto/US Army	Cell stacks/vehicle	20 KW	N_2H_4/KOH/Air	1967
Texas Inst.	Field power, military	1 KW	CO-H_2[d]/Mg_2CO_3/Air	1969
Pratt & Whitney	Residential power	10 KW	H_2[e]/H_3PO_4/Air	1971
Pratt & Whitney	Power module, DSSV[f]	20 KW	H_2/KOH/O_2	1972
Pratt & Whitney	Utility power	26 MW[g]	H_2[e]/H_3PO_4/Air	1972

(a) Most of the data are from Reference 66.
(b) Solid electrolyte: $(ZrO_2)_{0.85}(Ca)_{0.15}$.
(c) Steam reformed hydrocarbons and Pd-Ag duffusion.
(d) Partial oxidation of hydrocarbons.
(e) Steam reformed natural gas and shift reactor.
(f) Deep submergence, search and small object recovery vehicle.
(g) Design goal for electric utility applications.

a form suitable for the consumer, e.g., high-voltage ac power for electric utility companies. For the fuel-cell system to be cost effective, all three subsystems must have desirable cost efficiency and life characteristics. The present discussion will be limited to the fuel-cell system. Reference 67 discusses in detail the fuel-processing subsystem, and how this affects fuel-cell design and performance. It is recognized that a clean, hydrogen-rich fuel will be used in the fuel cells being developed, and that either air or oxygen will be used as the oxidant. If either hydrogen, or a hydrogen-rich gas, were used as a utility fuel then this could be directly fed to the fuel cell thus eliminating the fuel processor. However, impurities in this feedstock would need to be removed. For example, as little as 1 ppm of sulfur can detrimentally affect fuel-cell performance by poisoning the electrode catalysts.

A fuel cell is an electrochemical device for converting chemical energy to electrical energy. As a continuous energy-conversion device, it is similar to combustion systems (e.g., gas turbine/generator) in that electricity is produced as long as fuel and oxidant are supplied. As an electrochemical system it is similar to batteries. With a limited supply of fuel and oxidant it is like a primary battery; if the oxidant and/or fuel can be regenerated electrochemically, it is like a secondary or rechargeable battery (e.g., a regenerative fuel cell). The basic elements of any fuel cell are two electrodes and an electrolyte. The reactions in acid electrolyte (e.g., phosphoric acid solution) using oxygen and hydrogen (fuel) are

$$H_2 \rightarrow 2H^+ + 2e^- \text{ (negative electrode)}$$

$$1/2\ O_2 + 2H^+ + 2e^- \rightarrow H_2O \text{ (positive electrode).}$$

In alkaline electrolyte (e.g., potassium hydroxide solution) the reactions are

$$H_2 + 2OH^- \rightarrow + H_2O + 2e^- \text{ (negative electrode)}$$

$$1/2\ O_2 + H_2O + 2e^- \rightarrow 2OH^- \text{ (positive electrode).}$$

Fuel cells are designed to maintain a stable interface between the reacting gases and the electrolyte in the electrodes. In order to obtain the high-power densities (high reaction rate for fuel and oxidizer) required for practical fuel cells, catalysts (finely divided metal) are used in the electrodes. Some of the best catalysts are Group VIII metals such as platinum.

There are many possible combinations of fuel-cell design and and fuels, and the electrode catalyst requirements vary with the type of fuel cell and application. Fuel cells differ in the electrolyte used:--

Alkaline (KOH)

Acid (H_3PO_4 or H_2SO_4)

Ion-exchange membrane (IEM)

Solid electrolyte $\left[(ZrO_2)_{0.85}\ (CaO)_{0.15}\right]$

Fused salt ($Mg2CO_3$)

in the temperature of operation:--

Ambient temperature (20 C to 80 C)

Intermediate temperature (100 C to 250 C)

High temperature (300 C to 1000 C)

in the oxidant used:--

Oxygen (pure O_2)

Air (oxygen in air)

Hydrogen peroxide (H_2O_2)

and in the liquid or gaseous fuel used:--

Hydrogen (pure H_2, e.g., from water electrolysis)

Hydrazine (N_2H_4)

Methylalcohol (MeOH)

Carbon monoxide-hydrogen (CO-H_2)

Hydrocarbon (after steam reforming, partial oxidation, or thermal cracking)

Natural gas (after steam reforming).

In defining critical materials (primarily electrode catalysts), it is necessary to specify the application, type of fuel cell, and fuels with the realization that with evolving technology, substitutes for platinum group metal catalysts may be developed for economic reasons before the fuel cell reaches large-scale industrial use. As later explained, experiments to attain such an objective are currently under way; however, the work to date has not yet uncovered viable alternatives to the noble metal catalysts.

The fuel cell has several advantages over other energy conversion devices that will favor its use when the problems of present high

capital cost and limited life are resolved by current R&D. Some of these advantages are discussed below in relation to current trends in energy, environment, and economics.

In a fuel cell the electrochemical conversion of chemical to electrical energy occurs isothermally, unlike the heat engine, which operates between two different temperature levels. There is a limit to the efficiency of such engines as calculated from the Carnot cycle. Since the fuel cell has no such limitation it can, at least in theory, be a far more efficient device. A very high thermal efficiency*, up to 80 percent, can be achieved at low electrode current density (0.1 to 10 amp/ft^2) with a loss in efficiency as current density is increased due to voltage losses involved in the electrode reactions, and changes in resistivity of the electrolyte. Practical efficiencies based on the lower heating value of hydrogen as fuel are presently below 50 percent, as Figure 16 shows, which is taken from data supplied by Pratt & Whitney, Aircraft Division of United Aircraft Corporation. Acid fuel cells with air as the oxidant should be capable of attaining an efficiency of 55 percent in the near future, or 60 percent if oxygen is used as the oxidant. By 1990 a thermal efficiency of about 65 percent should be achieved.

Figure 16 shows that fuel cells are more efficient than alternative conventional systems for producing electrical power over a wide range of power outputs. Also, Figure 17 shows that fuel cells are more efficient than conventional electrical power producers when operated at part load (lower than nominal design power rating). An improvement in efficiency of even 10 percent over heat engines is important because of the increasing cost and limited supplies of fossil fuels. Thus, resurgence of interest in fuel cells in the 1970's is related to the energy crisis.

As shown in Figure 16, fuel cells do not have to be large to be efficient. The principle of modular construction enables large units to be constructed from the same basic components as smaller ones. This will lead to lower capital cost when large-scale production is undertaken. Also, many applications for stationary power require a gradual growth in power-output capability to meet future demand. Modular construction of fuel cells allows gradual additions to capacity in accordance with demand. Construction lead times are shorter for modular fuel cells and less capital is tied up during construction and in oversized units to meet future demand. The limited availability of capital and high interest rates will favor the modular fuel-cell approach over some of the conventional alternatives.

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*Efficiency = Heating value of electricity produced/ heating value of fuel feedstock.

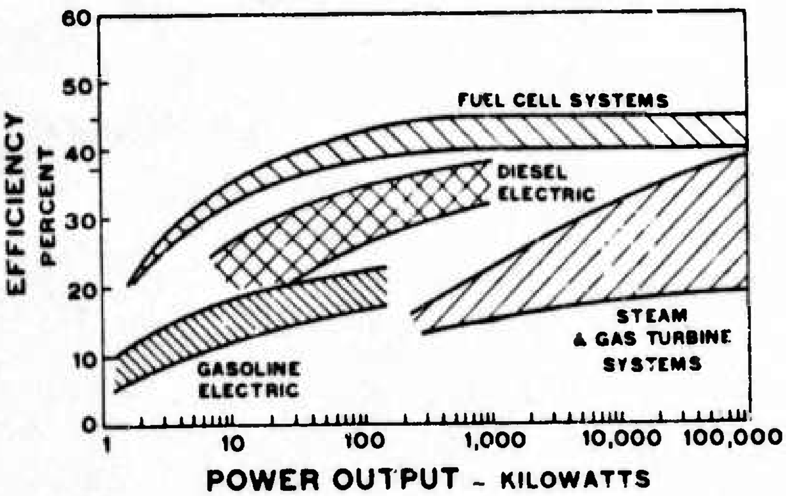

FIGURE 16. POWER GENERATION SYSTEM EFFICIENCY COMPARISON AS A FUNCTION OF POWER OUTPUT

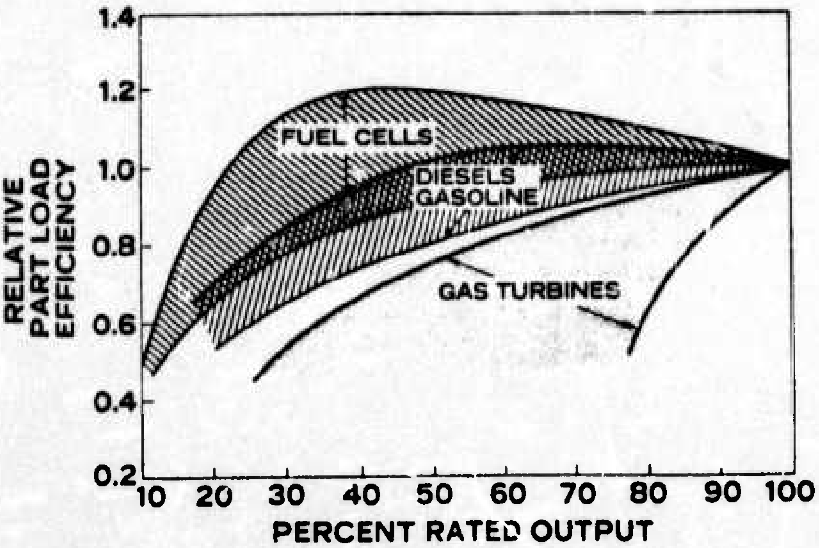

FIGURE 17. RELATIVE PART LOAD EFFICIENCY COMPARISON AS A FUNCTION OF POWER OUTPUT

Because both large and small fuel-cell systems can be constructed from standardized modules without greatly affecting performance, there results a flexibility which enables fuel-cell systems to be used effectively at any point in a total electric utility system. Installation could be made at any point from the central generating plant down to the individual consumer in his home, and the opportunity for transmission credits can arise which influences system economics.

The fuel cell has several environmental advantages. It has no moving parts; this leads to noiseless and reliable operation. The comparative simplicity of the electrochemical reactions make it likely that complete combustion can be achieved and nonoffensive exhaust products produced. Table 10 indicates the reduced air pollution possible with fuel cells. The increased capital cost for pollution-control equipment associated with heat-engine energy-conversion devices is narrowing the capital cost differential between these and fuel cells. Thus, fuel cells in the future will be more competitive in terms of capital cost. Fuel-cell systems will share these same advantages if the fuel-processing subsystem is a "closed-cycle" device and does not itself emit any pollutants. Some waste heat may be generated by the fuel-cell system. Depending upon the size of the system, this low-grade heat may or may not find application in such schemes such as district heating or integrated energy systems.

Industrial Applications for the Technology

Nonstationary Applications. There are many potential applications for fuel cells. Some are indicated in Table 9. The principal question is which application is expected to have a significant impact in terms of power-generating capacity and thus significant materials usage by 1990. Several of the applications (auxiliary power, portable power, and propulsion) can be discounted for the reasons given below to focus on the major potential market.

Auxiliary power is typified by space applications where the fuel cell is competitive in weight and size with batteries. For example, hydrogen/oxygen fuel cells have been used on Gemini, Apollo, the orbital laboratory, and will be used on the space shuttle. While sales to NASA represent a sizeable dollar market, the relatively small total amount of fuel-cell power needed is not likely to significantly affect the total amount of materials used even though up to 20 times as much platinum-group metal catalysts are used in the electrodes as would be economical for industrial applications. Fuel cells also have applications for unmanned satellite power supplies, but again the total capacity would be small.

Portable power supplies are used primarily in military rather than industrial applications. These needs are discussed in a subsequent

TABLE 10. MEASURED TYPICAL EMISSIONS FROM MODERN CENTRAL POWER STATIONS AND EXPERIMENTAL FUEL CELLS[73]

Pollutant	Typical Emission Level, lb/1000 kWhr: Gas-Fired Utility Central Station	Oil-Fired Utility Central Station	Coal-Fired Utility Central Station	Experimental Fuel Cells
SO_2	1	21	28	0-0.0003
NO_x	4	5	6	0.139-0.236
Hydrocarbons	3	8	20	0.225-0.031
Particulates	<1	1	1-2	0.00003-0

section. In the industrial sector, Engelhard Industries manufactures small H_2-O_2 fuel cells incorporating platinum-group metals, while Exxon-Alsthom market a small N_2H_4-O_2 fuel cell for portable electric welding equipment.

Vehicular propulsion applications are typified by electric vehicles for which prototypes have been developed (e.g., tractors, golf carts, and minibuses). An eletric van and an electric car, both powered by a hydrogen-oxygen fuel cell, have been demonstrated[68]. In these applications the fuel cell competes with the gasoline engine and with storage batteries. This could be a sizeable application if economical fuel cells are developed for electric vehicles. However, it is expected that battery-powered electric vehicles will be first commercialized in the period from 1975 to 1990. Hydrogen-fueled internal-combustion engines will probably be developed also in the period 1975 to 1990. The principal problem is finding a method for on-board storage of hydrogen. Hydrogen-air fuel cells could follow. However, economic fuel cells for electric vehicles are not expected to be developed sufficiently prior to 1990 if they use expensive platinum-group catalysts. Earlier development of fuel cells for electric vehicles would be dependent on development of non-noble catalysts that are less expensive and in less critical supply for the large transportation market. Thus, it does not appear that

significant amounts of platinum-group metals will be used in fuel cells for vehicular propulsion by 1990.

Stationary Applications. The remaining application of fuel cells is for stationary power generation which can be considered in four categories

- Central station power generation
- Dispersed utilization for peaking and load leveling
- Residential power supplies
- Remote siting.

These categories are discussed in the following sections.

The power utilities' interest in fuel cells was originally broad (base load, standby generation ["spinning reserve"], or backup power). However, the rising costs of fossil fuels needed for a "reformer-type" fuel cell do not favor fuel cells for future base load use in comparison to nuclear base load, even with a transmission credit for fuel cells of 60 percent of the projected capital investment. On the other hand, rising fossil fuel costs will favor the fuel cell over gas turbines for peaking energy because of the higher efficiency of the fuel cell over the gas turbine.

Central station power generation with coal or coal-derived fuel has been a major long-term objective of fuel-cell technology. The economics of competing with other major energy-conversion systems make this a long-range prospect beyond 1990. The high-temperature, solid electrolyte (ceramic) fuel cell and molten carbonate cell have been investigated with little success to date[69]. It is not likely that an economic fuel cell for central station power generation would utilize expensive platinum-group metals.

Fuel cells have application for remote siting (rural areas) primarily where the high efficiency in small sizes (1 MW or less) could offer economic advantages over other methods of generating electricity. However, it is not expected that rural siting would amount to 10 percent (in terms of installed power) of the potential application for fuel cells in industrialized areas. The recent trends in fuel-cell development have been directed to residential and dispersed utility system siting, with the latter representing the largest potential near-term use. An historical review of fuel-cell development supports this conclusion if one assumes that the most important potential application at the time receives the greatest proportion of R&D funding.

The \$50 million TARGET* program of P&WA and the gas utility industry was begun in 1966 and has proceeded through the second phase of field tests. The program, directed toward residential power ($\approx$12-kW size), is based on using steam-reformed natural gas to provide hydrogen for a hydrogen/air fuel cell with phosphoric acid electrolyte (in contrast to alkaline KOH electrolyte fuel cells for the space program where relatively pure hydrogen and oxygen are used). A principal limitation to commercialization was the capital cost which has decreased from more than \$1500/kW in 1968 to about \$450/kW in 1974 as Figure 18 shows. Forecasts are that costs will be \$200 to \$250/kW for commercial production[67]. However, because of shortage of natural gas it is doubtful that residential fuel cells will be commercialized until synthetic natural gas or hydrogen pipeline supplies are developed. Thus, significant markets for residential fuel cells are not expected before 1990.

The TARGET program provided a technology base for achieving the most likely commercialization of fuel cells for electric utility use which is the generation of peaking power at dispersed sites (substations). The siting for this application is intermediate in distance between the siting for central station power generation (>300 MW) and that for residential generation (12 kW), and the nominal power rating is intermediate, typically 26 MW. The current program of P&WA and nine utilities for dispersed power generation is termed FCG-1. The FCG-1 development, directed toward 26-MW fuel cells for dispersed siting on the electric utility system, is primarily based on the use of reformed liquid hydrocarbon fuels [e.g., No. 6 oil, No. 2 oil, and jet-grade kerosene (JR-5)] to provide the hydrogen for H_2/air fuel cells with phosphoric acid electrolyte.

Several types of equipment, all competitors to fuel cells, can be used by electric utilities to provide peak demand energy requirements above that supplied from the most economic base-load equipment. Gas turbines used for peaking (about 1000 hours/year) have relatively low first cost but high fuel costs and maintenance. Combined-cycle gas turbine systems which utilize the waste heat from the turbine in a steam cycle are more efficient but slightly higher in first cost. Because of their efficiency they are used more hours per day. Older steam-fired systems which are less efficient than newer base-load equipment are used for peak demands more hours per year (>3000 hours). Because of higher first cost but lower fuel cost and maintenance cost, fuel cells may be competitive for intermediate duty (1000 to 3000 hours/year). Also, because of their nearly constant efficiency under part load, fuel-cell systems could supply highly efficient spinning reserve capability[70].

In the intermediate duty range, a promising future alternative to "reformer-type" fuel cells is off-peak energy storage in batteries. A

*TARGET stand for Team to Advance Research for Gas Energy Transformation, Inc.

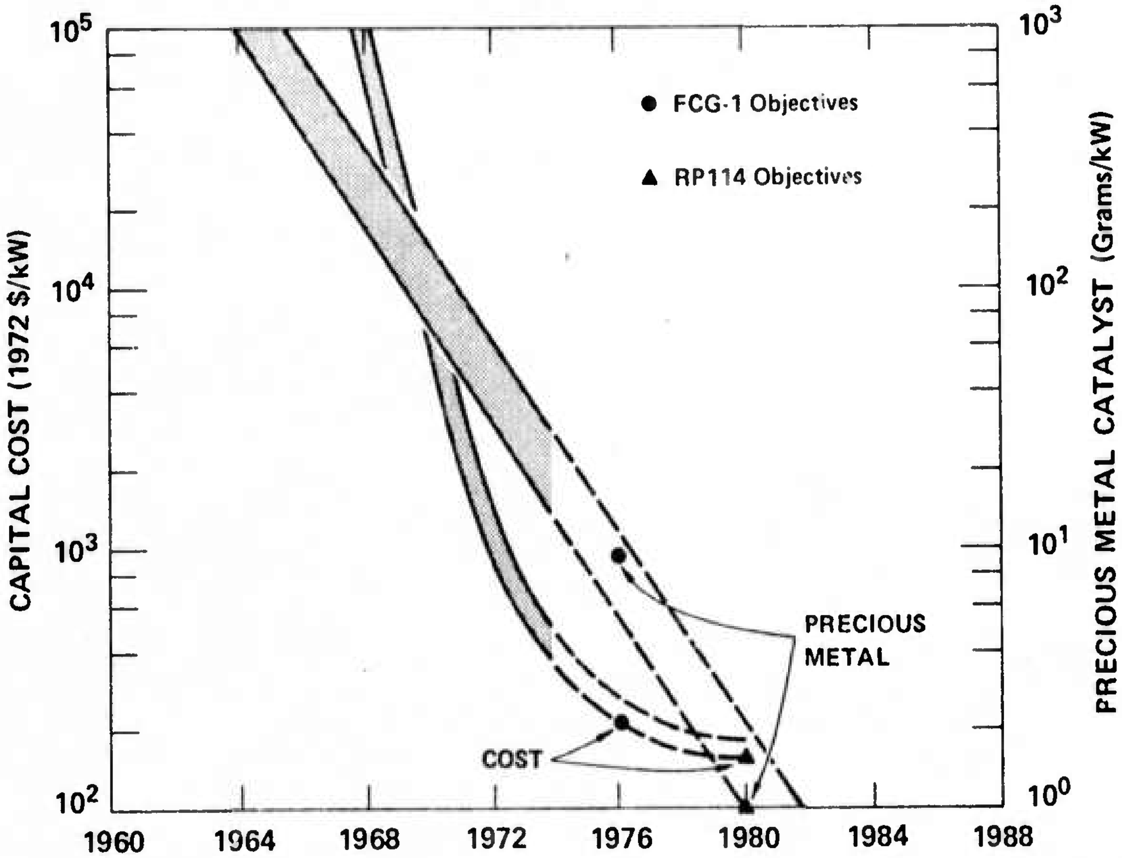

FIGURE 18. ECONOMIC PROGRESS FOR AIR-HYDROCARBON FUEL CELLS DEVELOPED BY UNITED TECHNOLOGIES [67]

Notes:

Capital cost is for complete powerplant (fuel to ac power).

Time scale is for engineering subsystems. System hardware would require an additional 4-5 years.

significant R&D effort is under way to develop the large battery installation needed for this application (e.g., advanced lead-acid batteries, or new batteries such as lithium-iron sulfide. In the latter category batteries for off-peak energy storage is the Battelle-proposed "water battery", which combines a hydrogen/oxygen fuel cell mode of operation and a water electrolysis mode of operation in a single unit. Lower cost, off-peak energy available at night and on the weekends will be used to regenerate hydrogen and oxygen which are stored for use during the peak power demand periods during the day to effect load leveling or peak showing.

The electric utility industry and the federal government are very interested in energy-storage technology. An assessment program is currently under way under the joint sponsorship of the Energy Research and Development Agency (ERDA) and the Electric Power Research Institute (EPRI) to evaluate possible energy-storage methods and indicate the directions for future R&D support. Concepts being considered include flywheels, superconducting magnets, compressed air, pumped water, storage batteries,and chemical systems based on hydrogen (e.g., water electrolysis/fuel-cell systems). Batteries and chemical systems are primary contenders at the present time. Batteries (e.g., lead-acid and lithium-iron sulfide) will not utilize platinum-group metals. As for chemical storage systems, platinum-group metals would be used in the "water battery". In the H_2/air fuel cell with the fuel reformer replaced by a conventional water electrolysis unit, platinum-group metals might not be used. (However, advanced, high-efficiency water electrolysis cells and acid fuel cells would use platinum-group metals.) Thus, batteries and chemical energy storage systems are in competition with each other and with "reformer-type" fuel cells for the application at dispersed sites (e.g., substations) on an electric utility system. Also, dispersed siting of power is in competition with existing central station peaking devices (gas turbines) and pumped-water storage.

Both batteries for energy storage and "reformer-type" fuel cells are being developed and it is difficult to predict which will capture the greater market by 1990. Energy-storage systems are favored by the increase in fossil fuel costs and the long-term trend toward lower-off-peak power costs. The cost of off-peak power is dependent on the mix of generating facilities. Today, off-peak power costs are high since base-load equipment is primarily coal or oil-fired steam generators. Nuclear-fueled generators have lower fuel costs, which leads to low off-peak power cost. As more nuclear capacity is installed and makes up a greater percentage of the base-load capacity, fuel cost and off-peak power costs will decrease. Thus, a principal determinant in cost is the rate of addition of nuclear capacity between now and 1990. Rising fossil fuel costs and the desire for energy independence favor nuclear power. If, as projected, off-peak power costs become lower beginning in the 1980-1985 period, energy storage will be favored using either batteries (no platinum metals),

H_2/air fuel cells, or the water battery. When low-cost off-peak power becomes available, the fossil-fuel processing subsystem can be replaced by a water electrolysis module to produce hydrogen for a hydrogen-oxygen fuel cell. An alternative to a separate water electrolysis module and separate fuel-cell module is the combined function unit (e.g., water battery) which could reduce significantly the amount of electrode catalysts required.

If nuclear capacity is not added as fast as projected, off-peak power costs will remain high which favors "reformer-type" fuel cells using oil in the near-term and coal-derived synthetic fuels in the future.

Projected Market Penetration by 1990 and Requirements for Critical Materials

Market Penetration. Annual additions of pumped-water storage capacity to meet generating requirements are projected to be about 1500 MW in 1980, increasing to 4000 MW by 1990[71] Similarly, it is projected that the annual addition of gas-turbine generating capacity for these applications will increase from 1000 MW (1980) to 5000 MW (1990)[71]. With additions to the total peaking capacity each year increasing from 2500 MW (1980) to 9000 MW (1990), it appears reasonable to assume that an average of 2000 MW per year of these additions could be "reformer-type" fuel cells, batteries, or water batteries depending on which proves to be the most economical. Thus, a total of 20,000 MW of fuel-cell or water-battery capacity installed by 1990 seems a likely estimate (see Figure 19) taken from Reference 72. In comparison, United Technologies estimates[73] that in the near-term about 15 percent of the U. S. annual new capacity can be supplied by fuel cells broken down as follows: (1) 10 percent of new apartment and commercial buildings, (2) 10 percent of obsolete urban stations, (3) municipal requirements below 40 MW, and (4) 10 percent of private utility new-capacity additions.

The current FCG-1 Phase I program is funded at \$42 million (28 million from 9 utilities and \$14 million from United Technologies). An additional \$7 million will be used to develop a demonstration unit ($\approx$1 MW) by about 1977. If the specified performance is achieved, United Technologies has "provisional initial orders" for 56 units of 26 MW each (total $\approx$\$250 million) with deliveries orginally scheduled for 1978 to 1980[74]. If successful, the initial orders ($\approx$1500 MW total) could grow to 20,000 MW total installed capacity by 1990.

A principal problem would be the demand for platinum for other new uses. For example, the use of platinum-group metals in catalytic

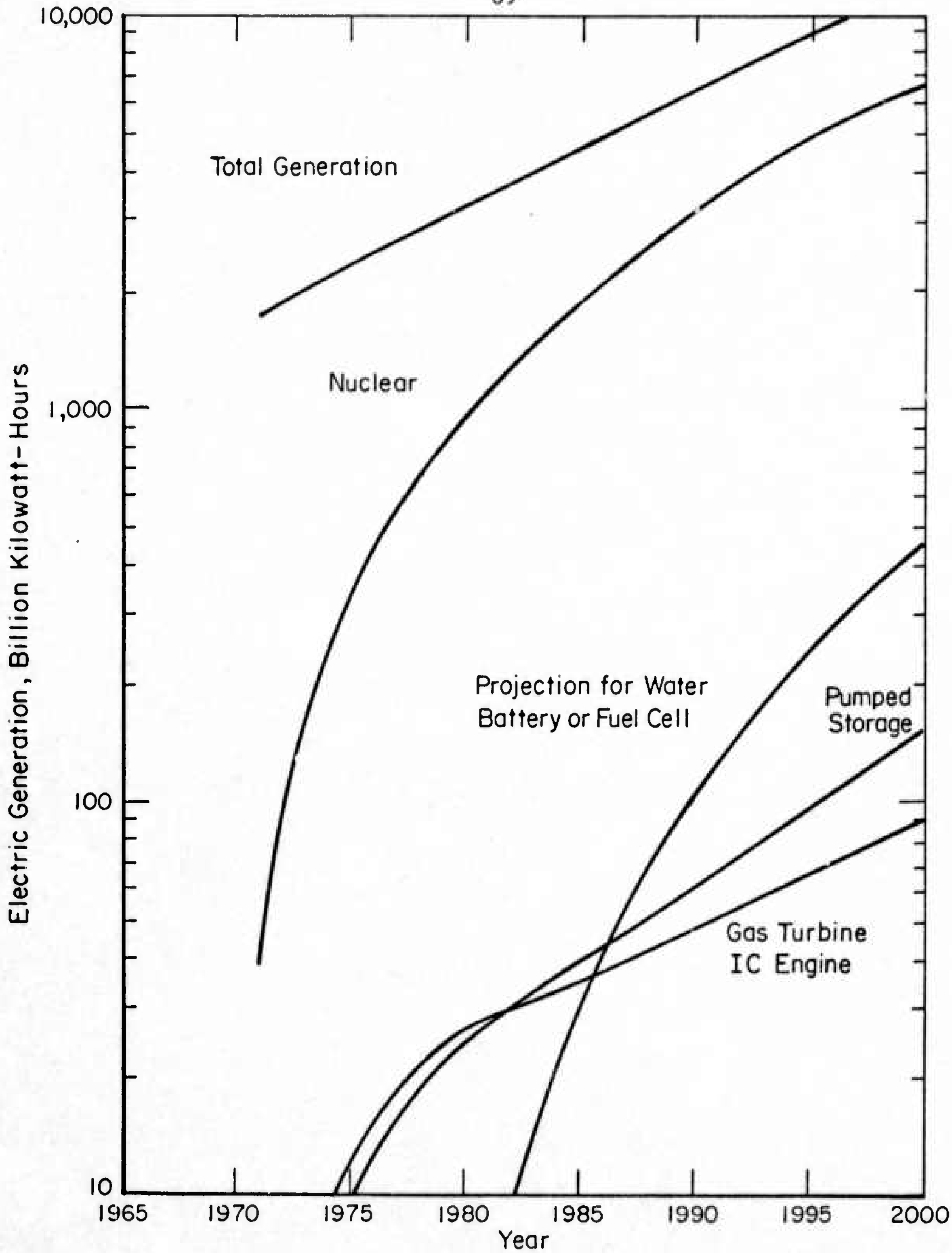

FIGURE 19. PROJECTED GENERATION OF ELECTRICITY AS A FUNCTION OF TIME

(Curves represent additions to base-load fossil-fuel generation. The curves for total, nuclear, pumped storage, and gas turbine engine generation were prepared from data in Reference 75. The curve for water batteries or fuel cells is from Reference 72.)

exhaust mufflers for automobiles has created a surge in demand.* This has been met by supply. However, if other demands cause shortage of available platinum metals and cause increases in price, the amount used as catalysts in fuel cells will have to be decreased in order to remain competitive with other energy-conversion devices. If the amount of platinum-group catalyst used cannot be reduced, the market for fuel cells will be smaller.

Critical Materials. The materials in critical supply involved in this technology will be platinum-group metals (platinum, palladium, iridium, and rhodium) used as electrode catalysts. The other platinum-group metals (ruthenium and osmium) are not often mentioned. Gold and silver are also used as catalysts but the supply problem is less critical.

The quantity of critical materials that will be needed for fuel cells depends on (1) the application potential in terms of installed power capacity (kw), and (2) the cost of the specific material ($/tr oz) which determines the amount that can be economically used in fuel-cell electrodes considering the amount of the fuel cell capital cost that can be devoted to electrode catalysts. For example, assume that there will be 20,000 MW of installed fuel-cell capacity for peak-power generation at electric utilities by 1990. Assume that platinum costs $5/gram ($155/tr oz) and that $75/kw (dc output) of the capital investment in fuel cells can be allotted to platinum catalysts. The amount of platinum in use for this application by 1990 could be:

$$20{,}000 \text{ MW} \left(\frac{1000 \text{ kw}}{\text{MW}}\right)\left(\frac{\$75}{\text{kw}}\right)\left(\frac{1}{\$5/\text{g}}\right) = 3 \times 10^8 \text{ grams } (9.6 \times 10^6 \text{ tr oz}).$$

The technical feasibility of fuel cells is well established and the principal impediment to large-scale commercial use is the capital investment for users. The fuel cell is in competition with conventional established methods of converting hydrocarbons to electricity. Thus, the capital investment (first cost) for fuel cells must be competitive with alternatives (e.g., gas turbine) using similar fuels in order for fuel cells to penetrate the market significantly. A higher capital investment for a fuel cell can be allowed when a sufficiently higher efficiency of fuel conversion can be demonstrated, which would lower operating costs, and where there are other advantages that can

*The price of palladium skyrocketed from $40/tr oz in mid 1972 to over $150/tr oz in mid 1974, while platinum prices increased "only" 50 percent from $100 to $150/tr oz. The reason has not been confirmed.

be assigned a monetary value (e.g., dispersed siting, low environmental pollution, low noise level, modular construction in smaller sizes). For example, current capital cost estimates of future (1980) fuel-cell systems for peaking power based on large sizes (26 MW) are

Fuel cell	\$85 - \$150/kw
Reformer	\$25 - \$45/kw
dc/ac converter	\$60 - \$105/kw
Total system	\$170 - \$300/kw.

Of the fuel-cell subsystem cost, an appreciable portion is for the electrodes. If the allowable cost for electrode catalysts is assumed to be in the range of \$25 to \$100/kw, a limitation is placed on the amount of catalyst used because of the cost of precious-metal catalysts, apart from considerations of future availability. A numerical example will illustrate this fuel-cell engineering-design approach. Again, assume that \$75/kw of dc output can be spent on catalysts for the fuel-cell electrode. The catalyst utilization and electrode cost depend on the power density attainable at rated power output. Assume a power density of 250 watts/ft^2 can be achieved (e.g., 333 amp/ft^2 at 0.75 volt). The specific cost for electrode catalysts is

$$\text{specific cost} = (\$75/\text{kw}) \left(\frac{\text{kw}}{1000 \text{ watts}}\right) (250 \text{ watts/ft}^2) = \$18.75/\text{ft}^2.$$

Assume that the catalyst is platinum at \$5/gram (\$155/tr oz). The weight of catalyst that can be used is

$$\left(\frac{\$18.75}{\text{ft}^2}\right)\left(\frac{1}{\$5/\text{gram}}\right) = 3.75 \text{ g/ft}^2 \ (4 \text{ mg/cm}^2).$$

For the assumptions given above, an allowance of \$75/kw is equivalent to a catalyst loading of 15 g/kw, which is the loading projected by United Technologies for the first generation FCG-1 fuel cells delivered (Figure 18). Figure 18 indicates that United Technologies' catalyst loading in 1974 was about equivalent to 20 g/kw, indicating that approximately a 25 percent improvement in performance is required for the assumed capital cost of the fuel cell.

Conceptual design and economic studies at Battelle[72] allowed for the use of platinum and palladium in the electrodes to achieve the

combination of long life (5 to 20 year-goal) and high efficiency (50 to 75 percent goal). This study provided some estimates of platinum-group metal use.

Assuming no new demands that would affect supply and prices, it was estimated that if beginning in the year 1980, the annual world production rate of platinum-group metals (predominantly platinum and palladium) were increased by 1 percent each year, the added production would be sufficient for 20,000 MW of installed water-battery capacity by the year 2000 based on the use of 385 tr oz of platinum and 52 tr oz of palladium per MW of electric power output (about 13.5 g/kw). The total amount of platinum-group metals in 20,000 MW at 437 tr oz/MW is $\approx 10 \times 10^6$ tr oz. If the 20,000-MW capacity is achieved by 1990 rather than by 2000, an increase in the annual world platinum-metals production of 2 percent per year rather than 1 percent per year would be required. Because of the flexibility of the world platinum industry, such increases in production capacity do not appear to be unreasonable.

These figures relating U. S. needs to an increase in world output of platinum-group metals suggest that the U. S. demand would not have a serious effect on the supply situation for these metals on a worldwide basis. However, it is important to note that the 10×10^6 tr-oz requirement for 20,000 MW of installed capacity is equal to five times the 1974 U. S. consumption for platinum-group metals[39]. Assuming that this demand is distributed evenly over a 10- or 20-year period (1980 to 1990 or 1980 to 2000), this demand would represent an additional yearly requirement equal to 25 or 50 percent of the 1974 U. S. consumption.

This large potential demand, particularly in view of the dependency of the U. S. on imports from sensitive countries for 86 percent of its platinum-metal supply (1974)[53] are the basis for the criticality judgment. In regard to the latter point, it should be noted that there is no identified potential at the present time for domestic production. The major sources of platinum are the U.S.S.R, South Africa, and the United Kingdom. The world supply of palladium is virtually monopolized by the U.S.S.R. One comment about availability may be interjected at this time, however, and that is because the platinum metals are corrosion resistant there are negligible materials losses. Fuel cells, therefore, will have considerable salvage values associated with these catalyst materials. Fuel-cell installations may therefore be viewed as decentralized "stockpiles" of platinum metals.

Figure 18 shows that the utilization of precious-metal catalysts per kW of capacity (hence, fuel cell cost if the catalyst price remains constant) is projected to decrease with calendar time, as anticipated developments are achieved. Figure 19 shows that the projected installed capacity increases with time, which has a counter balancing effect with regard to total catalyst requirements. Table 11, compiled from these data, indicates that over the time period of interest the

TABLE 11. TOTAL PLATINUM-METAL CATALYST REQUIREMENTS AS A FUNCTION OF UTILIZATION AND INSTALLED CAPACITY

Year	Utilization[a], g/MW	Installed Capacity[b], MW	Materials Requirement, g
1980	2×10^3	3.0×10^3	6×10^6
1985	0.2×10^3	30×10^3	6×10^6
1990	0.02×10^3	100×10^3	2×10^6

(a) Extrapolated from Figure 18, assuming future technical advances are achieved.
(b) From Figure 19, 1000 hour-per-year operation assumed.

weight of catalyst materials required will remain constant or decrease. The impact on world reserves may be lessened if these projections are found to be correct. However, it should be emphasized that the projected decreases in catalyst usage per kw of output are predicated on technical advances that have not yet been achieved.

Other factors may also serve to limit the amount of platinum metals required. For example, not all fuel-cell concepts require precious-metal catalysts. The P&WA RP114 program is investigating molten carbonate fuel cells, among other concepts. Molten carbonate cells use nickel as the catalyst material[76]. At the high temperatures of operation, the reaction rates are sufficiently fast that expensive catalysts are not required. The Universal Oil Products Company, under contract to the U. S. Army Mobility Equipment Research and Development Center, is investigating the use of proprietary nonmetallic materials incorporating pyrolized hydrocarbons. Although not active as fuel-cell electrodes themselves, when used in conjunction with noble metal catalysts appreciable reactivity is observed[77]. There is the possibility that by using these materials, catalyst loadings may be reduced by more than an order of magnitude over the current state of the art for low-temperature fuel cells.

Department of Defense Requirements

As is known, fuel cells were used successfully in the Gemini and Apollo space programs. The basic technology involved in the latter programs is being further developed for consideration in meeting special military applications in space, on land, and underwater. The potential

quantitative needs for materials, critical or otherwise, to meet such requirements are very small in relation to the possible total needs for materials if fuel cells were to be incorporated in the electrical power industry. Furthermore, the technology would be tailored quite differently to meet these special applications since the space and military systems characteristics, and the economics involved, differ considerably from those of potential commercial systems.

One specific military need which relates more directly to the potential commercial systems, particularly residential fuel cells, is the Department of the Army requirement for a

> Silent Lightweight Electric Energy Plant (Short title: (SLEEP - ROC*). It calls for general-purpose, mobile power units to be used in ground tactial situations (78). The specific desired characteristics and planning goals are:
>
> - 91,000 units,
> - Initial operating capability date is 1981, but to be fully distributed to the tactical organizations by 1990,
> - One-half to 10 kilowatt output per unit (for a total of 300 megawatts in procurement),
> - Have low thermal and infrared signatures,
> - Be reliable and cost effective,
> - Total life of 10,000 operating hours with a mean time between overhaul of 3000 hours.
>
> The fuel cell is considered by the Army to be a most promising candidate to meet the requirement. They feel it has a potential for performing better than standard field motor generator sets in meeting the specifications and in life-cycle costs, because of greater reliability, longer total life, and lesser maintenance (78). They are working directly on reducing costs through considerable reduction in platinum loadings in fuel-cell electrodes (perhaps an order or magnitude below current state-of-the-art electrodes which are understood to require about 20 grams of platinum per kw of output) (77).
>
> As for needs for platinum to meet the total 300 megawatt requirement, the Army performed a study several years ago. It indicated the peak demand for production of

*ROC = Required Operational Capability.

the 91,000 units over a 10 year span would not exceed 3 percent of the annual U.S. consumption of platinum in the early 1970's.[78]

The Army has identified a particular problem which they are addressing in the development program for the SLEEP system. This concerns the fuel processor. The Army envisages that clean fuels such as natural gas and light naptha will not be available to tactical units. The military will likely rely on fuels available through logistic channels, such as gasoline, diesel fuel, and jet fuel. The carbon, sulfur, and lead in these fuels react corrosively with the combustors in the fuel processor at the high temperatures involved (1500 to 2000F). As a consequence, the life of the combustors is less than desired. The Army is looking into a number of research and development approaches which should solve the problem in time for the projected production. Another possible solution might be in methanol, a clean fuel, becoming available as a logistic fuel[78].

Potential Procurement and Development Problem Areas for the Department of Defense

Availability of Platinum. In relation to total U.S. demand, it would appear that DoD requirements for platinum for fuel cells are not large. On the one hand, it could therefore be rationalized that, in this instance, the DoD needs for platinum will be met within the U.S. action to seek a solution to the situation represented by the present Bureau of Mines forecasts. These forecasts indicate that it is unlikely that domestic production will ever satisfy much of the domestic demand[39]. In 1974, 86 percent of the U.S. demand for platinum-group metals was imported[53], coming primarily from the U.S.S.R., South Africa, and the United Kingdom. On the other hand, it could be argued that DoD should not be complacent about materials availability since platinum-group metals are already on the critical materials list and being stockpiled. At the present, no other fuel cell catalysts besides platinum have been identified as viable substitutes. DoD should therefore consider:

Supporting/identifying U.S. policies which will insure the availability of platinum-group metals to U.S. industry.

Establishing procurement incentives which will insure availability of platinum to meet DoD needs if the competitive needs for the material increase - as the market picture clarifies for commercialization of fuel cells and for other uses such as catalysts in automotive emission control systems.

Research to reduce the catalyst loading in present fuel cell electrodes from about 20 g/kw to 1 or 2 g/kW, or less.

Continuing the search for alternative catalyst materials which are not on the critical materials list.

Improving manufacturing methods to reduce fabrication, hence overall costs. Automatic procedures have advantages in economy over hand-operated and batch operations.

Engineering the systems such that the catalyst materials can be readily salvaged and used in the next generation of fuel cell systems (the "stockpiling" effect).

<u>Development of Fuel Processor to Meet SLEEP Requirement</u>. The DoD should determine whether or not any additional research and development avenues should be pursued to provide an adequate fuel processor for the conditioning of logistic fuels for fuel cell system operation in the field.

Lasers for Communications and Materials Processing

by

Barry P. Fairand

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Technical Description of the Technology

The word "laser" is an acronym for light amplification by stimulated emission of radiation. The emitted radiation is electromagnetic in nature and is generated by placing an active (amplifying) medium in a resonant cavity. The active material can be energized--"pumped"--in various ways, including electrical discharge of electrodes, initiation of chemical reactions, and discharge of flash tubes. Lasers are normally classified by the type of active medium used in the resonant cavity and cover a spectrum of materials from gases to solids. Among those employing gas as the active medium are carbon dioxide, argon, and nitrogen gas lasers, while three typical solid-state lasers are ruby, yttrium-aluminum-garnet (YAG) doped with neodymium, and glass doped with neodymium. The wavelength band of these systems ranges from the far infrared to the ultraviolet.

A distinctive property of laser radiation that separates it from conventional sources of electromagnetic radiation is its coherence. Because of this property, the laser is a highly monochromatic, directed source of radiation which exhibits very small beam divergence with distance. These properties allow the laser radiation to be collected by a simple lens system and focused down to a very small spot size. The laser power densities generated in the focal region far exceed those that can be generated by any conventional source of radiation and are only rivaled by electron-beam devices. However, unlike electron beams, laser energy can be propagated over rather large distances in air or other gases with little attenuation, thus permitting the laser beam to be sent to remote work areas, receiver units, targets, etc.

To gain an appreciation for the tremendous power densities that can be achieved with a focused laser system, assume an energy output of 10 joules in a single laser pulse of 1-millisecond (10^{-3}sec) duration (a level readily achievable in many commercial systems). The peak power during this pulse is

$$\text{watts} = \text{joules/second}; \ \frac{10}{0.001} = 10{,}000 \text{ watts.}$$

If the focused spot diameter is 50 micrometers, the power density is over 5×10^8 watts per square centimeter. This level of power density can vaporize any known material. With the continuing development of lasers of ever increasing energy capability, it is possible to achieve these high-power densities with larger focused spot diameters and even

with defocused beams. This can have important implications in broadening the applicability of lasers particularly in material processing applications.

The coherence and monochromaticity of laser energy provide additional benefits that are difficult or impossible to obtain in other radiation sources. For example, holographic images are based on the coherence property of the laser. In the optical spectrum, the laser is the only source of radiation with sufficient intensity to provide high-quality holographic images. The highly monochromatic nature of the laser make it an ideal tool for spectroscopic analysis and selective initiation of chemical reactions.

The ease of controlling the laser beam and directing it to a precise location at the exact time of interest have justified its use in applications such as retina attachment, alighnment, surveying, and precision machining of miniature semiconductor parts.

With the development of rugged, high-power (multikilowatt) laser systems, lasers are no longer limited to high-technology applications, but are beginning to compete with other sources of energy strictly on the basis of their thermal energy capacbility. Such lasers are now being put to use in the heavy construction and automotive industry to surface heat treat large parts and for deep-penetration welding and cutting of large sheets of thick metal plate.

Because of its suitability for use in a relatively large number of applications, along with its low cost and simplicity in design, the helium-neon laser has become the most widely used laser system today. This trend is expected to continue at least for the next few years. The helium-neon laser is closely followed in use by various types of carbon dioxide lasers, both pulsed and continuous wave (CW). Carbon dioxide systems operate at rather high efficiencies, e.g., 15-20 percent, which make them particularly attractive in today's energy-conscious society. Added to this is a simple and rugged design with the present capability of delivering tens of kilowatts of optical power.

The neodymium-doped yttrium-aluminum-garnet (neodymium-YAG) laser is the most efficient solid state laser although its efficiency is presently limited to about one-tenth that of the carbon dioxide systems. However, the neodymium-YAG laser is, in general, a more compact system and its low efficiency compared to the carbon dioxide laser is partly compensated for by a wavelength one-tenth that of carbon dioxide. Because of its shorter wavelength, the neodymium-YAG laser can be focused down to smaller spot sizes than can carbon dioxide lasers and also interacts more efficiently with metals and certain nonmetals. Hence, it is often favored in materials processing applications. CW neodymium-YAG systems presently are operated up to about 1 kilowatt power. Pulsed neodymium YAG systems have peak powers of up to at least 400 kilowatts, and average powers of a few hundred watts.

Ruby, the original laser developed by Maiman in 1960, and neodymium-glass offer high energies per pulse but suffer from a low duty cycle and a low efficiency of electrical-to-optical energy conversion. Both lasers will continue to be used during the future years, but their use, except in high-technology applications, is expected to decrease with time.

Gallium arsenide is the principal semiconductor laser used today. It represents a compact and efficient device. By varying the diode composition it is possible to tune these devices, although the tuning range is narrow. Tuning has obvious implications in some applications. Other tunable lasers mainly consist of organic dyes.

A class of laser systems is presently under development which, by 1990, could possibly supplant some of the laser systems already discussed. These systems are commonly referred to as chemical lasers. The radiation emitted by chemical lasers is released during a chemical reaction that takes place at an elevated temperature, within the laser. Within the military establishment, presently there is an effort underway to develop systems of this type. Five to ten years ago similar circumstances surrounded the development of high-power carbon dioxide lasers. Thus, if history repeats itself as is often the case, then in 5-10 years high-power chemical lasers will be available for nonmilitary uses if they are found to be applicable.

A positive factor in favor of the use of chemical lasers is the high efficiencies that, in theory, can be attained from such systems. Efficiencies greater than 50 percent and, in some instances, approaching 100 percent appear possible. However, chemical lasers possess drawbacks that may limit their usefulness for nonmilitary applications. First, the chemical reactions that have been found to possess lasing capability typically are corrosive and often times toxic. Second, the experimentally observed efficiencies are much smaller than the predicted values because of parasitic oscillations or other competing reactions. Finally, the lasers are not closed-cycle systems, e.g., they are flow systems that require replenishment of the lasing material as it is consumed by the chemical reactions. Thus, it appears that chemical lasers, as they are presently known, will find limited industrial application by 1990.

Industrial Applications for the Technology

The various present and potential (by 1990) industrial applications for lasers can be divided into seven different areas. They include

- Information handling
- Materials processing
- Communications
- Medical applications
- Holography
- Measurement techniques and alignment
- Chemical applications.

Information Handling. The use of the laser in the area of information handling undoubtedly will have the most effect on the society of 1990. Information handling covers the point-of-sale scanner area, video disc players, computer printout systems, and facsimile transmitters and copiers. It is easy to envision supermarkets, department stores, and other retail sales organizations using point-of-sale decoding devices. Hundreds of thousands of lasers would be required to meet this need. Imagine that by 1990, video disc players may find the same market as today's color television sets! Because of its low cost, stability, and compactness, the helium-neon laser probably will be used in the majority of these systems. In some of the other applications where higher powers are required, the argon laser may be more suitable.

Materials Processing. The area of materials processing includes operations such as cutting, drilling,welding, scribing, and heat treating of materials either to alter their shape or to change their properties. Because of its high efficiency and capability of high-power output, the carbon dioxide laser has become the most widely used laser system in this application area. This trend is expected to continue for the next 10 to 15 years.

The other laser system that has found rather extensive use is neodymium-YAG. Neodymium-YAG lasers probably will capture even a greater percentage of the materials processing application area during the coming years. Ruby and neodymium glass are also used to process materials; however, their use is expected to fractionally decrease betwen now and 1990.

Communications. The use of lasers in the communications area is beginning to take hold. By 1990, short-range optical data links using fiber optics are expected to be a relatively common means of communication, particularly in areas of high population density. In particular, the telephone industry is very much interested in and is planning for the use of fiber optics in interoffice trunk lines, where they would substitute for the standard copper wire paired cable.(79,80,81) The light source could be either a laser [perhaps the gallium arsenide semiconductor laser because of its ability to be modulated directly, compactness, very small emitting area, efficiency, and ability to achieve (by a slight change in chemical composition) a wavelength that matches an attenuation minimum

of the fiber], or a light-emitting diode (LED). Research to develop light sources with increased lifetime and output is being carried out by RCA Corporation and by Texas Instruments, Inc.[82]

The projected economic advantage of fiber optics in this application was presented in detail on May 15, 1975, by representatives of General Telephone and Electronics Corporation (GTE).[80,83] The advantages are based on the first cost (installed cost) of the cable, repeaters, and other equipment. In addition, GTE expects increased reliability; decreased maintenance requirements; decreased susceptibility to water damage, lightning, crosstalk, and electromagnetic interference; with respect to metallic twisted pair cable. Field evaluation of an optical fiber line is to be carried out by GTE in 1976, in the region of a participating GTE telephone company.[80] By the year 1980, GTE expects the use of glass-fiber cable to be economically competitive with twisted-pair copper cable "as a means for providing many new circuits in the telephone company trunk plant." Data transmission will be the primary need.

Bell Telephone Laboratories is understood to agree with the projections of GTE.[81] The interest of Bell Telephone Laboratories in fiber-optic communications is shown further by the large amount of research that they have carried out in this area. Bell Laboratories points out that another advantage of fiber-optic cables is that, because such cables are much smaller in diameter than metallic wire paired cables for the same capacity, they can be installed between existing wire cables in telephone conduits where there is no space for additional wire cables.[81] Thus, the use of fiber optic cables can often eliminate the cost of excavating streets in order to place new conduit when additional lines are required. Such costs, especially in large cities, can involve many millions of dollars even when relatively short distances are involved.

Additional advantages of fiber-optic communications cable are given in the section on Department of Defense requirements.

Medical Applications. In the medical area, most people are familiar with the use of the laser for attaching detached retinas. Several hundred argon lasers presently are being used to perform this operation. By 1990, a few thousand lasers probably will suffice to meet the needs of this application. The laser also is beginning to be put to use in the medical world in a different application which should see substantial growth by 1990. Because the laser beam can be focused down to a small spot size and accurately directed to the area of interest, it represents a precision surgical tool. "Bloodless surgery", where the intense heat generated in the focus of the laser cauterizes the incision, is presently being used in simple operations such as removing tonsils, and is expected to find much more extensive use over the next 15 years. The carbon dioxide laser probably will be selected in most instances to perform this type of surgery.

<u>Holography</u>. In the early 1960's, when the laser was first used to produce three-dimensional images, many thought a major new application area would quickly develop. Most of these applications did not materialize over the ensuing years. However, commercial holography is now maturing and we can expect to see it put to use in significant ways over the next 15 years. Perhaps the most promising application of holography is in the area of nondestructive evaluation, referred to as holometry. This includes, for example, aerodynamic testing, defect analysis, and quality control of manufactured products. Of these, the last application will require the largest number of laser systems. Another use for holography that is receiving considerable attention is detection and characterization of particles. Such studies are primarily concerned with laboratory testing, and, therefore, are not expected to entail the need for a large number of laser systems. Holographic techniques also are being studied for use in optical data processing and in information storage and retrieval. Therefore some overlap exists between this area and the information handling area.

The helium-neon and argon lasers appear to be the best choices for continuous wave holographic techniques. Ruby is presently the best selection in those cases where time resolved holography is required but it probably will be largely replaced in the future with frequency doubled neodymium-YAG which emits in the green portion of the optical spectrum.

<u>Measurement Techniques and Alignment</u>. Laser metrological techniques are beginning to gain acceptance in the machine tool area. They provide a noncontact, highly reliable means of gauging and inspecting piece parts. Wherever speed or accuracy is desired, a laser measurement scheme is likely to be applicable. The construction industry has been, and is expected to continue to be, a large customer of lasers for alignment, squaring, and leveling applications. Another measurement area where lasers are rapidly replacing conventional methods is in mapping and surveying applications. Speed and accuracy are again the major advantage of the laser over standard practices.

The stability, low cost, and reliability of the helium-neon laser make it the most used system in the area of measurement techniques and alignment. Over long distances where more power is required, the argon laser may be more suitable.

<u>Chemical Applications</u>. Chemical applications encompass such things as isotope separation, laser-induced photochemistry, and absorption spectroscopy. There presently is a strong interest in all of these areas and this interest is expected to continue well into the future. Much of this work will be conducted in the laboratory and, therefore, will not necessitate construction of a large number of laser systems by 1990. Tunable dye lasers and semiconductor lasers are expected to find the widest use in this area.

Laser fusion, another type of chemical application, also is not expected to require large quantities of laser materials by 1990.

Projected Market Penetration by 1990 and Requirements for Critical Materials

All of the above application areas will undergo substantial growth over the next 15 years. The area of information handling probably will undergo the greatest growth and make a substantial penetration into its respective market area. This probably will be followed by the communications field.

At first glance, it may appear that some of the laser materials could be labeled as critical materials by 1990. However, under closer scrutiny, none of the lasers that are expected to form the bulk of those used by 1990 will pose a problem insofar as acquisition of the raw materials needed in their manufacture. Although millions of lasers could be used in the information handling area, supplies of helium, neon, and argon gas needed in their construction will far exceed the demand. Gallium arsenide may be required for hundreds of thousands of lasers in the communications field; however, the demand for gallium arsenide in this application appears to represent only a relatively small fraction of that required in the manufacture of light-emitting diodes for electronic devices.

Materials Processing. In the mid-term report on this program, which represented the results of the screening phase of this study, neodymium-YAG was presented as being a potentially critical material. Since this is a very-high-purity low-imperfection single-crystal material, the 1974 production of which was estimated to be about 30 pounds or less,* the possibility of production capacity for neodymium-YAG not being available to meet increasing demands in the materials processing area was identified. The materials processing area presently uses no more than several hundred YAG lasers. Over the next 15 years, the use of lasers in this area will continue to grow and may represent several thousand systems by 1990.

Upon closer examination, no evidence was found to indicate that there will be a lack of production capacity for neodymium-YAG by 1990. Specifically, personal contacts with two of the three major manufacturers of neodymium-YAG laser crystals uncovered no indications of a possible shortage of production capacity for this material.(84,85) The equipment that is used to make other laser crystals such as ruby and

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* An industry source later confirmed this estimate.

sapphire can be used to make neodymium-YAG if the market demand increases. Moreover, at present there are between 20 and 40 machines ("grow stations") idle, that could be used immediately to manufacture relatively large amounts of neodymium-YAG. This equipment was previously used to make synthetic gems, the market for which lasted only about 2 or 3 years.[84,85]

The single reservation to the conclusion that probably there will be no lack of production capacity neodymium-YAG by 1990 pertains to the extent to which the neodymium-YAG laser will be used in the communications field. At the present time, it appears that semiconductor lasers and gas lasers will be the major laser systems used in this area.

Whereas lasing materials per se may not pose a problem by 1990, some of the interfacing optics used in the laser systems may become critical materials either through lack of supply as a result of dependence on foreign sources or a lag in the development of the necessary technology to produce large amounts of the material. Included in this list are certain crystals and special optical glasses. Calcite is a highly birefringent natural crystal that is used for modulators, polarizers, and isolators. Another crystal, rutile, possesses a high index of refraction which makes it suitable for use in the communications field to modulate signals onto the laser carriers. Brazil is a large supplier of natural crystals to the United States. The extent of the potential problem with natural crystals is difficult to evaluate since substitute materials in the form of synthetic crystals may circumvent the problem before 1990. Special optical glasses, as wave guide materials for the communications area, are covered in the following section.

Communications. The major laser application area that may experience a critical materials problem by 1990 is communications. Accordingly, the subsequent discussion will focus on this area in order to assess its impact on critical materials by the year 1990.

The principal critical material in laser communications is the very-high-purity silica glass fiber that is used in fiber optic linkups in order to avoid excessive attenuation of the signal. The longer the distance over which the signal must be carried, the greater the importance of low attenuation in the fibers. For telephone use, it appears that fibers in the attenuations of 5 dB/km ± 2 dB/km will be required [86] in order to minimize the number of repeaters needed in the line and achieve the desired system economics. The requirements for the fiber material, and the possible materials criticality problem, will be similar regardless of whether the light source is a laser or an LED.

GTE expects that, by 1978 or 1979, a standard cable practice for interoffice trunk lines will have been developed.[79] Their projection is that such cable will be introduced starting in 1980, with a build-up during the 1980's so that (by the year 1990) 20 percent of

interoffice telephone company trunking in the United States will involve fiber optic cable.[79] Based on this projection, approximately 6 million miles of low-loss fiber will be required by 1990.[79] Assuming that the currently popular 0.005-inch-diameter fiber is used, this length of fiber will weigh about 700,000 pounds.

At present, only one U.S. company (Corning Glass Works) markets such fiber. It is acknowledged that Corning is the world leader in this area.[87] They are presently in the pilot-plant stage of production, with an annual production capacity of "thousands of kilometers",[86] e.g., perhaps 1000 miles or more. (One-thousand miles of 0.005-inch-diameter silica fiber weighs about 120 pounds.) ITT Electro-Optical Products Division also has developed low-loss fibers for this application and is preparing to market them.[88] Bell Telephone Laboratories has also developed a low-loss fiber, but information on the exact status of their work is not available. Moreover, at least two copper cable companies are seriously studying the possibility of drawing glass fibers from the billet and/or making cable from glass fibers.

Corning Glass Works has indicated that there would be no problem in meeting the production needs of the telephone companies.[86] Inasmuch as telephone companies work on long lead times, Corning visualizes that they would have time to increase their manufacturing capacity to meet the demand. This would involve developing improved, more economical manufacturing procedures.

The current selling price of low-loss optical fibers in lengths of 100 km is \$1.50 per meter.[86] Corning has indicated that, when the sales volume reaches 100 million dollars, the price will have decreased to about $\$0.05 \pm 0.02$ per meter.[86] Inherent in this extreme cost reduction is the development of improved, economical manufacturing procedures for large-volume production.

The bases for the judgment of possible criticality of low-loss fiber optic materials are that

- It will be necessary for fiber production capacity to increase by perhaps 1000-fold by 1990 in order for the projected needs of telephone companies to be met.
- Improved fiber-manufacturing procedures will have to be developed in order to achieve a selling price that may be acceptable to telephone companies.

Nevertheless, it should be emphasized that a shortage of production capacity is by no means certain. Corning Glass Works, and probably others, are very much interested in this market and indicate that they are prepared to develop improved manufacturing procedures and

increase production capacity. But it is understood that this is predicated on an initial sales volume of $100 million dollars.(86)

Department of Defense Requirements

Fiber-optic communication has a number of advantages that are of much interest to the military. Among these are the following:(89,86,79,88)

(1) Resistant to radiofrequency interference. Thus, they may be used in environments that are electronically "noisy".

(2) No tendency to radiate radiofrequency signals.

(3) Signal not disturbed by electromagnetic pulses or other effects from nuclear explosions (nuclear hardenability).

(4) Very large band width.

(5) Less attenuation than with metallic paired cable, so repeaters can be spaced further apart.

(6) Security (privacy) of communication.

(7) Low crosstalk.

(8) Much smaller size than metallic paired cable. Accordingly, fiber optic cable is easier to deploy. Also, either more bits can be carried in cable of a given diameter, or a smaller diameter cable can be used for the same bit rate.

(9) Lack of necessity for a ground return, thereby avoiding possible ground loop problems.

(10) Weight savings, e.g., a 20:1 savings in weight compared to 26-pair local distribution cable.

Military applications of fiber-optic communications are being studied in the Army, the Navy, and the Air Force.(89,90,79,86) The U.S. Army's interests are in three categories, as follows: (89)

- Information transfer systems on Army bases
- Distribution systems on command posts in the field
- Interconnecting systems between command posts. Lengths of up to 8 km are required, without the need for a repeater.

In the latter two applications, which are tactical, the cables must be portable, rugged, and strong. Field deployment in the early 1980's is projected.(89) Presumably, nontactical use on Army bases would precede this.

The U.S. Navy's interest in fiber optic communications may be classified as follows:(90,79,89)

- Undersea cable for ocean surveillance. An extremely low-loss fiber (e.g., 2 dB/km or less) is preferred for this application. This is the largest U.S. military application for fiber optics.
- Internal information transfer on ships. Service evaluations are being carried out aboard the aircraft carrier, Kitty Hawk, (closed-circuit television) and the cruiser, Little Rock, (six telephones).
- Information transfer on airplanes and helicopters. A service evaluation of fiber optic navigation and delivery systems is being carried out on the A7D attack aircraft.

The U.S. Air Force is also studying the use of fiber optic information transfer systems on aircraft.(89) They are examining the use of such systems not only on new aircraft but also as retrofits on existing aircraft.

Possible Procurement and Development Problem Areas for the Department of Defense

It is anticipated that by the year 1990, laser communications will be widely used by the DoD for various military applications and thus will compete directly with the civilian market for the same materials and subsystems. This may create a procurement problem for DoD, if sufficient production capacity is not available to satisfy both the military and the industrial markets. However, the needs of both the military and the industrial sectors for material with the same properties has the potential advantage of resulting in a lower price for the material. In order to establish the market demand that is needed to stimulate development by industry of economical mass-production manufacturing procedures, it is recommended that consideration be given to coordinating the quantitative needs of the three services for the material. (It is understood that a triservice committee on fiber optics presently exists, but for the purpose of standardizing connector design and other systems features.)

Since the properties required in the fibers are essentially the same in military and industrial applications, and industry has shown the ability to produce such material, no fiber development problems are envisioned for DoD. Nevertheless, a number of other development problem areas may exist, as follows:

(1) Systems engineering problems associated with the use of fiber optic communications in remote areas where the same lines are used for both power supply and communication.(89)

(2) Interface problems at the locations where fiber optic lines are connected to metallic wire cable lines. (89)

(3) The strength, crush resistance, and other properites required in undersea cable for ocean surveillance represents a problem area. However, the U.S. Navy currently is developing a cable with the requisite properties. (90)

(4) The development of fiber optic cables that are portable, rugged, and strong for Army field use, could also present a problem to the DoD.

REFERENCES

(1) Anonymous, "Kaiser Aluminum, Jamaica Set Accord in Bauxite Dispute", The Wall Street Journal, November 21, 1974, p 18.

(2) DoD Materials Shortages Workshop, Washington, D.C., January 14-16, 1975.

(3) First National Conference on Materials Availability/Utilization, Chicago, Illinois, January 27-29, 1975.

(4) Hopkins, R.K., "The Electric Ingot Process", AIME Electric Furnace Proceedings, 6, 1948, pp 91-105.

(5) Paton, B. Ye., and Medovar, B. I.,"Electroslag Remelting of Steels in Water Cooled Molds",Avtomaticheskaya Svarka, (11),1958, pp 5-15.

(6) Latash, Yu. V., and Medovar, B. I., Electroslag Melting, Izdatelstvo, Moscow, 1970.

(7) Wahlster, M., and Schumann, R., "A Contribution to the Electroslag Remelting of Large Forging Ingots", Proceedings of the Fourth International Symposium on Electroslag Remelting Processes, Tokyo, Japan, June 7-8, 1973, pp 337-345.

(8) Hirabayashi, Y., "Electroslag-Remelting Furnaces", Kinzoku Butsuri, 17 (17), 1971, pp 44-48.

(9) Wahlster, M., "The ESR Process - What Is Its Position Today", Proceedings of the Fifth International Symposium on Electroslag and Other Special Melting Technologies, Pittsburgh, Pennsylvania, October 16-18, 1974, pp 40-61.

(10) Holtzgruber, Dr. W., INTECO, Brück und der Mür, Austria, personal communication to Joseph G. Dunleavy, Battelle-Columbus, May, 1975.

(11) Wahlster, M., "Review of Current Applications of ESR and Its Products", Journal of Industrial Engineering, September-November, 1973, pp 40-61.

(12) Paton, B. E., Medovar, B. I., and Boiko, G. A., "Outlook for the Application of Electroslag Casting", Proceedings of the Fifth International Symposium on Electroslag and Other Special Melting Technologies, Pittsburgh, Pennsylvania, October 16-18, 1974, pp 239-250.

(13) Ujief, A., "Manufacture of Contour Sided Rings by the Rotary Withdrawn ESC Process", Proceedings of the Fifth International Symposium on Electroslag and Other Special Melting Technologies, Pittsburgh, Pennsylvania, October 16-18, 1974, pp 251-270.

(14) Holtzgruber, W., "Possibilities and Limitations to Influence the Structure of ESR Ingots and Properties of ESR Products" , Proceedings of the Fifth International Symposium on Electroslag and Other Special Melting Technologies, Pittsburgh, Pennsylvania, October 16-18, 1974, pp 70-90.

(15) Wahlster, Professor M., Leybold-Heraeus AG, Hanau, West Germany, personal communication to Joseph G. Dunleavy, Battelle-Columbus, May, 1975.

(16) Bhat, Dr. G. K., Carnegie-Mellon Institute, Pittsburgh, Pennsylvania, personal communication to Joseph G. Dunleavy, Battelle-Columbus, April, 1975.

(17) Stupak, L., "Electroslag Furnace ESR-40", Proceedings of the Fifth International Symposium on Electroslag and Other Special Melting Technologies, Pittsburgh, Pennsylvania, October 16-18, 1974, pp 62-70.

(18) Hayashi, Dr. C., ULVAC Corporation, Tokyo, Japan, personal communication to Joseph G. Dunleavy, Battelle-Columbus, February, 1975.

(19) Hoyle, Geoffry, British Steel Corporation, Sheffield, England, personal communication to Joseph G. Dunleavy, Battelle-Columbus, May, 1975.

(20) Zweben, Carl H., "Hybrid Fiber Composite Materials", Proceedings of the 1975 International Conference on Composite Materials, Geneva, Switzerland, and Boston, Massachusetts, April 7-11 and April 14-18, 1975, respectively.

(21) Sturgeon, Donald L. G., "Performance Basis for the Application of Aramid Fiber Reinforcement, E. I. du Pont de Nemours & Co., Inc., Wilmington, Delaware, no date.

(22) "Metal-Matrix Composites: Status and Prospects", National Materials Advisory Report No. NMAB-313, December, 1974.

(23) Ford, Curry E., Vice President, Carbon Products Division, Union Carbide Corporation, New York, N. Y., personal communication to Dr. Bryan R. Noton, Battelle-Columbus, June, 1975.

(24) Tannenbaum, Jeffrey A., "Carbon Fibers Find Diverse New Uses, but Can You Afford a $1200 Bicycle?", The Wall Street Journal, July 17, 1975, p 34.

(25) Keuhl, Donald K., Manager of Applications Engineering, Composite Materials Corporation, A subsidiary of the Aluminum Company of America, Broad Brook, Connecticut, personal communication to Dr. Bryan R. Noton, Battelle-Columbus, July, 1975

(26) Prendergast, Thomas,Manager, Composite Products, AVCO Systems Division, Lowell, Massachusetts, personal communication to Dr. Bryan R. Noton, Battelle-Columbus, July, 1975.

(27) Selected personnel of E. I. du Pont de Nemours & Co., Inc., Wilmington, Delaware, personal communications to Dr. Bryan R. Noton, Battelle-Columbus, June, 1975.

(28) Davis, LeRoy W., "Evaluation of Aluminum/Graphite Composite Materials", First Quarterly Technical Progress Report, Contract N00017-73-C-4313, Naval Ordnance Systems Command, Washington, D. C., October, 1973.

(29) Jordan, Charles E., "Advanced Composites are Here to Stay", presentation at the New York University Conference on Composite Materials, March, 1974.

(30) Goldsworthy, Brandt, President, Goldsworthy Engineering, Inc., Torrance, California, personal communication to Dr. Bryan R. Noton, Battelle-Columbus, July, 1975.

(31) Smith, J. L., Jr., Kirtley, J. L., Jr., and Thullen, P., "Superconducting Rotating Machines", IEEE Transactions on Magnetics, MAG-11 (2), March, 1975, pp 128-134.

(32) Mole, C. J., and Sterrett, C. C., "A Superconducting Machine for Central Station Power Generation", Proceedings of the American Power Conference, 35, 1973, pp 1035-1047.

(33) Appleton, A. D., "Superconducting d.c. Machines - Concerning Mainly Civil Marine Propulsion but With Mention of Industrial Applications", IEEE Transactions on Magnetics, MAG-11 (2), March, 1975, pp 633-639.

(34) Forsyth, E. B., "Progress at Brookhaven in the Design of Helium-Cooled Power Transmission Systems", IEEE Transactions on Magnetics, MAG-11 (2), March, 1975, pp 393-396.

(35) Hess, G. K., Jr., Ziurys, E. J., and Beard, D. S., "Applications of Superconductivity in the Controlled Thermonuclear Research Program", IEEE Transactions on Magnetics, MAG-11 (2), March, 1975, pp 135-140.

(36) Fraas, A. P., "Materials Problems in the Design of Magnetically Confined Plasma Fusion Reactors", Nuclear Technology, 22 (1), April, 1974, pp 10-19.

(37) Hassenzahl, W. V., Baker, B. L., and Keller, W. E., "Economics of Superconducting Magnetic Energy Storage Systems for Load Leveling: A Comparison with Other Systems", LA-5377-MS, 1973, 20 pp.

(38) Laverick, C., "Helium Supply and Demand in Future Years", IEEE Transactions on Magnetics, MAG-11 (2), March, 1975, pp 109-112.

(39) Commodity Data Summaries, 1975, Bureau of Mines, U. S. Department of the Interior, January, 1975.

(40) Takai, T., "Present Supply-Demand Situation of Niobium", Cryogenics, 14 (6), June, 1974, pp 301-306.

(41) McDonald, W. K., Chief of Manufacturing Engineering, and Curtis, Clarence, Process Development Engineer, Teledyne Wah Chang Albany, Albany, Oregon, personal communication to Dr. Curtis M. Jackson, Battelle-Columbus, July, 1975.

(42) Garrity, Keith R., Vice President and General Manager, Fansteel, Inc., North Chicago, Illinois, presentation at the First National Conference on Materials Availability/Utilization, Chicago, Illinois, January 27-29, 1975.

(43) Garrity, Keith R., Vice President and General Manager, Fansteel, Inc., North Chicago, Illinois, personal communication to Dr. Curtis M. Jackson, Battelle-Columbus, July, 1975.

(44) Rosner, Carl, President, Intermagnetics General Corporation, Guilderland, New York, personal communication to Dr. Curtis M. Jackson, Battelle-Columbus, July, 1975.

(45) Gregory, Dr. Eric, Corporate Director of Research and Development, AIRCO, Inc., Murray Hill, New Jersey, personal communication to Dr. Curtis M. Jackson, Battelle-Columbus, July, 1975.

(46) Levedahl, Dr. W. J., Propulsion and Auxiliary Machinery Department, Naval Ship Research and Development Center, Annapolis, Maryland, personal communication to Dr. Curtis M. Jackson, Battelle-Columbus, July, 1975.

(47) Jokl, Dr. L., U. S. Army Mobile Equipment Research and Development Center, Fort Belvoir, Virginia, personal communication to Dr. Curtis M. Jackson, Battelle-Columbus, July, 1975.

(48) McLean, A. F., "Ceramics in Automotive Gas Turbines", Bulletin of the American Ceramics Society, 52 (5), 1973, pp 464-466.

(49) McLean, A. F., "Ceramics in Small Vehicular Gas Turbines", Ceramics for High Temperature Applications, Proceedings of the 2nd Army Materials Conference, Hyannis, Massachusetts, November, 1973, pp 9-36.

(50) McLean, A. F., "The Application of Ceramics to the Small Gas Turbine", ASME Paper No. 70-GT-105.

(51) McLean, A. F., "The ARPA/Ford All Ceramic Turbine Development Program", NATO/CCMS Symposium on Low Pollution Power Systems Development, Dusseldorf, West Germany, November 4-8, 1974, pp 233-257.

(52) Katz R. N., and Lenoe, E. M., "Ceramic Rotors for Small Automotive Gas Turbine Engines - Technology Assessment", AMMRC SP 75-4, May, 1975.

(53) Morgan, Dr. John D., Jr., "World Outlook for Critical Materials in the 1970's", paper presented at the First National Conference on Materials Availability/Utilization, Chicago, Illinois, January 27-29, 1975.

(54) "Ceramic Materials and Components for Small Automotive Gas Turbine Engines", Technology Assessment and Implementation Plan FY76-81, Prepared by Planning Directorate, Army Materials and Mechanics Research Center, Watertown, Massachusetts, April 30, 1975.

(55) Katz, Dr. R. Nathan, Chief, Ceramics Research Division, U.S. Army Materials and Mechanics Research Center, Watertown, Massachusetts, personal communication to Dr. Curtis M. Jackson, Battelle-Columbus, July, 1975.

(56) Wright, T. R., and Niesz, D. E., "Improved Toughness of Refractory Compounds, NASA Report No. CR-134690, October 11, 1974.

(57) Seltzer, M. S., Clauer, A. H., and Wilcox, B. A., "High Temperature Creep of Ceramics", Battelle-Columbus Laboratories, Second Annual Report under WPAFB Contract No. F33515-73-C-4111, February 28, 1975.

(58) McCoy, L. G., and Wright, T. R., Battelle-Columbus Laboratories, unpublished data.

(59) Komeya, K., and Noda, F., "Aluminum Nitride and Silicon Nitride for High Temperature Gas Turbine Engines", Presented at SAE Automotive Engineering Congress, Detroit, Michigan, February 25 - March 1, 1974, Paper No. 740237.

(60) Sebestyen, T. M., Wagner, C. E., and Lewis, L. D., "Report on the EPA/AAPSD - Chrysler Corp. Gas Turbine Development Program", NATO/CCMS Symposium on Low Pollution Power Systems Development, Dusseldorf, West Germany, November 4-8, 1974, pp 190-210.

(61) Sthyr, K., Ford Motor Company, Dearborn, Michigan, personal communication to Dr. Thomas R. Wright, Battelle-Columbus, April, 1975.

(62) Torti, Dr. M. L., and Alt, Dr. Neal, Research Manager and Technical Director, respectively, Industrial Ceramics Division, Norton Company, Worcester, Massachusetts, personal communication to Dr. Curtis M. Jackson, Battelle-Columbus, July, 1975.

(63) Johnson, Edward, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, personal communication to Dr. Curtis M. Jackson, Battelle-Columbus, July, 1975.

(64) Banks, Dr. William F., Deputy Director, Research, Development, and Engineering, U. S. Army Tank Automotive Command, Warren, Michigan, personal communication to Dr. Curtis M. Jackson, Battelle-Columbus, July, 1975.

(65) Hayes, Charles W., and Zabierek, Captain Donald, "Turbine Vane Ceramic Endwall", Journal of Aircraft, 12 (4), April, 1975, pp 247-252.

(66) O'Sullivan, J. B., "Historical Review of Fuel Cell Technology", Proceedings of the 25th Annual Power Sources Conference, 1972, p 151.

(67) Fickett, A. P., "An Electric Utility Fuel Cell: Dream or Reality?", presentation at the American Power Conference, April 21-23, 1975, Paper No. 103.

(68) Crowe, B. J., "Fuel Cells: A Survey", NASA Special Publication No. SP-5115, 1973, p 80.

(69) Sverdrup, E. F., "Project Fuel Cell", R & D Report No. 57, Research and Development Center, Westinghouse Electric Corporation, Pittsburgh, Pennsylvania, Final Report on Contract No. 14-01-0001-303 to the Office of Coal Research, August, 1970.

(70) Podolny, William H., Fuel Cell Program Manager, Power Systems Division, United Technologies Corporation, South Windsor, Connecticut, personal communication to Dr. Curtis M. Jackson, Battelle-Columbus, July, 1975.

(71) Anonymous, Electrical World, September 15, 1974, p 55.

(72) Clifford, J. E., Brooman, E. W., Sulzberger, V. T., and El-Badry, Y. Z., "Economic and Technical Evaluation of a Water Battery Concept for Energy Storage on an Electric Utility System", Final Report to the Battelle Energy Program, 1974.

(73) United Technologies, Power Systems Division, "Fuel Cells for Utility Service", April 30, 1975.

(74) Anonymous, "Pratt and Whitney, Nine Utilities 26-MW Fuel Cell Program", Electric Light and Power, 52 (2), January, 1974, p 2.

(75) Nassikas, J. N., "National Energy Policy: Directions and Developments", Proceedings of the American Power Conference, 1973, p 4.

(76) Synthetic Fuels Panel, "Hydrogen and Other Synthetic Fuels", Report No. TID-26136, 1972, p 98.

(77) Welsh, L. B., Hervert, G. L., Spielberg, D. H., and Youtsey, K. J., "Carbonaceous Catalysts for H_3PO_4 Fuel Cells", Universal Oil Products Company, Des Plaines, Illinois, First Interim Progress Report on Contract DAAK02-75-C-0011, to the U.S. Army Mobile Equipment Research and Development Center, Fort Belvoir, Virginia, March, 1975.

(78) Gillis, E., Chief, Electro-Chemical Division, U. S. Army Mobile Equipment Research and Development Center, Fort Belvoir, Virginia, personal communication to James O. Frankosky, Battelle-Washington, June, 1975.

(79) Fulenwider, Dr. John, Senior Scientist, GTE Laboratories, Inc., Waltham, Massachusetts, personal communication to Dr. Curtis M. Jackson, Battelle-Columbus, June, 1975.

(80) Fulenwider, John, and Killinger, George, "Optical T-Carrier Systems on Glass-Fiber Cable: A Promising New Technology", Telephony, 188 (22), June 2, 1975, pp 34-37ff.

(81) Bickle, David, Bell Telephone Laboratories, Murray Hill, New Jersey, personal communication to Dr. Curtis M. Jackson, Battelle-Columbus, June, 1975.

(82) Anonymous, "10-km Optic Waveguide by Corning", Electronic News, July 21, 1975, p 21.

(83) Smith, Ray, and Gregory, Lon, "Charlotte Showcase Hits the Jackpot", Telephone Engineering and Management, June 15, 1975, pp 54-58.

(84) Beeman, J. J., Marketing and Sales Manager, Crystal Products Department, Union Carbide Corporation, San Diego, California, personal communication to Dr. Curtis M. Jackson, Battelle-Columbus, July, 1975.

(85) Kass, C., Sales and Marketing Manager, Synthetic Crystal Products, Allied Chemical Corporation, Morristown, New Jersey, personal communication to Dr. Curtis M. Jackson, Battelle-Columbus, July, 1975.

(86) Lucy, Charles J., General Manager, and Bielawski, W. Bart, Supervisor - Market Development, Telecommunication Products Department, Corning Glass Works, Corning, New York,personal communication to Dr. Curtis M. Jackson, Battelle-Columbus, July, 1975.

(87) Anonymous, "Competition in Low-Loss Fiber Optics", Electro-Optical Systems Design, 7 (2), February, 1975, p 19.

(88) Kao, Dr. C., Staff Scientist, ITT Electro-Optical Products Division, Roanoke, Virginia, personal communication to Dr. Curtis M. Jackson, Battelle-Columbus, July, 1975.

(89) Dworkin, Dr. Lawrence, U. S. Army Electronics Command, Fort Monmouth, New Jersey, Personal communication to Dr. Curtis M. Jackson, Battelle-Columbus, July, 1975.

(90) Albares, Dr. Donald, Electro-Optics Technology Division, Navy Electronics Laboratory Center, San Diego, California, personal communication to Dr. Curtis M. Jackson, Battelle-Columbus, July, 1975.

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U.S. INDUSTRIES AND COGNIZANT BATTELLE SPECIALISTS

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U.S. Industry	Emerging Technologies	Battelle Specialists Involved
Aerospace and Space Systems	Dirigibles Superhuge cargo planes Air cushion vehicles - hovercraft	Elmer J. Bradbury Dr. Joe H. Brown, Jr. Dr. Stanley H. Gelles Walter S. Hyler Dr. Thomas E. Leontis Victor Levin Dr. Bryan R. Noton Richard G. Ollila
Chemicals and Chemical Processes	Fire retardant chemicals Use of titantium tubing in highly corrosive environments New methods for increasing the octane rating of gasoline Hydrodesulfurization of crude oil Recovery of metals from heavy crude oil Coal gasification Enzyme production Monomolecular films	Walter K. Boyd Dr. Elton H. Hall William M. Henry Dr. Douglas W. Hissong David M. Jenkins Edward S. Lipinsky
Communications	Optical communications Laser communications Large scale digital transmission of commercial data Use of picturephones for business conferences Use of microprocessors in the home Computer monitoring and control of processes Optical character readers	Joseph W. Benson George J. Falkenbach Emmett R. Reynolds William D. Stuart
Construction	Fiber-reinforced concrete Pre-engineered buildings for home units	Rolland B. Guy Dr. David R. Lankard
Electronics/ Electrical	Batteries for energy storage and automobiles Light-emitting diodes Large-scale integrated circuits Infrared detectors High-temperature electronics Traveling-wave tubes Microwave generators Liquid crystal displays	Dr. Eric W. Brooman John E. Clifford Winston H. Duckworth Dr. Harold M. Epstein Dr. Barry P. Fairand Gordon B. Gaines Donald J. Hamman Frank J. Jelinek Charles S. Peet

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Chemicals and Chemical Processes	Fire retardant chemicals Use of titantium tubing in highly corrosive environments New methods for increasing the octane rating of gasoline Hydrodesulfurization of crude oil Recovery of metals from heavy crude oil Coal gasification Enzyme production Monomolecular films	Walter K. Boyd Dr. Elton H. Hall William M. Henry Dr. Douglas W. Hissong David M. Jenkins Edward S. Lipinsky
Communications	Optical communications Laser communications Large scale digital transmission of commercial data Use of picturephones for business conferences Use of microprocessors in the home Computer monitoring and control of processes Optical character readers	Joseph W. Benson George J. Falkenbach Emmett R. Reynolds William D. Stuart
Construction	Fiber-reinforced concrete Pre-engineered buildings for home units	Rolland B. Guy Dr. David R. Lankard
Electronics/ Electrical	Batteries for energy storage and automobiles Light-emitting diodes Large-scale integrated circuits Infrared detectors High-temperature electronics Traveling-wave tubes Microwave generators Liquid crystal displays	Dr. Eric W. Brooman John E. Clifford Winston H. Duckworth Dr. Harold M. Epstein Dr. Barry P. Fairand Gordon B. Gaines Donald J. Hamman Frank J. Jelinek Charles S. Peet

U.S. Industry	Emerging Technologies	Bettelle Specialists Involved
Energy	High-voltage direct-current power transmission Gas centrifuge separation process Gas nozzle separation process Liquefied natural gas operations Use of zircalloy tubing to clad nuclear fuel elements Direct conversion of energy by magnetohydrodynamics	Lambert Bates Dr. Eric W. Brooman John E. Clifford Dr. Richard S. Denning Winston S. Duckworth Donald H. Frieling Dr. Elton H. Hall Frank J. Jelinek David M. Jenkins William M. Pardue Meyer Pobereskin John D. Waddell Dr. Thomas R. Wright
Food and Agriculture	Use of methyl parathion as an insecticide	Gerald W. Collings Dr. John H. Litchfield
Forest Products	Oxygen/alkali systems for the pulping and bleaching of wood Whole-tree pulping	Dr. W. James Frederick
Machinery	Automation	Francis W. Boulger Howard C. Davis John T. Herridge Thomas M. Trainer
Materials	Continuous casting	Elmer J. Bradbury Winston H. Duckworth Dr. Stanley H. Gelles Frank J. Jelinek Dr. David R. Lankard Dr. Thomas E. Leontis H. Dana Moran Dr. Bryan R. Noton
Medicine and Biomedicine	Use of stainless steel for blood catheters Ceramic bone replacements Use of vitallium and titanium alloys as orthopedic implants	Dr. Richard D. Faib

U.S. Industry	Emerging Technologies	Battelle Specialists Involved
Mining and Minerals Processing	Fused chloride electrolysis process	Dr. William Goldberger
Ocean Engineering	Ocean mining of manganese nodules Offshore mining	Arthur J. Coyle
Transportation	Microcomputers (microprocessors) for automobiles Levitated trains	Walter E. Chapin John B. Day John T. Herridge Victor Levin James P. Loomis Dr. Alfred C. Robinson Dr. Thomas R. Wright
Waste Treatment and Environmental Control	Waste-to-energy systems Recycling of materials from refuse Desulfurization of flue gases from electric power plants	Philip R. Beltz Dr. Robert H. Cherry, Jr. John B. Hallowell Dr. Douglas W. Hissong

APPENDIX B

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APPENDIX B

PERSONAL CONTACTS

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APPENDIX C

ADDITIONAL EMERGING TECHNOLOGIES IDENTIFIED
IN FIFTEEN U.S. INDUSTRIES

APPENDIX C

ADDITIONAL EMERGING TECHNOLOGIES IDENTIFIED IN FIFTEEN U.S. INDUSTRIES

Selection Criteria Used and Factors Applied in Selection Process

The technologies identified in the screening process as appearing to have the greatest impact on requirements by 1990 for critical materials were to be selected for in-depth studies. Three criteria were applied in making these selections:

(1) The quantity of critical materials required or supplied by the emerging technology.

(2) The degree of criticality of the particular critical materials required or supplied by that technology.

(3) The degree to which the emerging technology was expected to penetrate the market by the year 1990. [Among the factors to be considered in projecting the market penetration of the technology would be (a) any obvious energy intensivity of the basic processes involved in the technology and (b) any obvious negative effect of the technology on the environment.]

To apply these criteria, it was necessary to identify critical materials and to rate the degree to which they could possibly become critical. The following factors were considered in the identification and rating of critical materials:

(1) Extent to which the United States relies on imported supplies of the material (a) at present and as currently projected and (b) in the future, on the basis of emerging technologies.

(2) Extent of needs for the material by the Department of Defense (a) at present and as currently projected and (b) in the future, on the basis of emerging technologies.

(3) Degree of competition between industry and the Department of Defense for the available supply of the material (a) at present and as currently projected and (b) in the future, on the basis of emerging technologies.

(4) Possible existence in the United States of a significant shortage of production capacity with which to process the material into the required form (a) at present and as currently projected and (b) in the future, on the basis of emerging technologies.

(5) Basic availability of the material (a) ore reserves and (b) amount produced per year.

(6) Availability of any obvious substitute materials.

Obviously, not all of these factors could be covered in detail for each emerging technology identified when the U.S. industries were preliminarily scanned. Rather, information that was readily available from Battelle specialists, selected government and industrial reports, and personnel of The Rand Corporation (RAND) and Stanford Research Institute (SRI) who are involved in related studies for ARPA was used to make value judgments on the basis of these factors.

ADDITIONAL EMERGING TECHNOLOGIES IDENTIFIED IN FIFTEEN U.S. INDUSTRIES

(These technologies either overlap with the six selected for further research or were not so selected because they did not sufficiently meet the applicable selection criteria)

Industry	Emerging Technology	Brief Description of Technology	Criticality Consideration(s)	Basis for No In-depth Analysis
Aerospace and Space Systems	Dirigibles	For the transport of heavy large-volume cargo, such as nuclear reactor components and space shuttles. Dirigibles with volumes of about 30 million cubic feet are under consideration.	None apparent at this time.	It is not presently envisaged that there would be any types/amounts of materials or processes involved which significantly affect the critical materials situation and would therefore impact adversely on the DoD.
	Super Huge Cargo Planes	The use of super huge cargo planes on the order of one million pounds or more gross weight to carry freight at reduced costs. Aircraft of these sizes will require the use of lightweight structural materials such as composites, magnesium and possibly beryllium.	Graphite or organic-fiber composite materials will be critical materials. The aircraft have obvious potential as military transports.	(Composite materials were selected for further study)
	Air-Cushion Vehicles-Hovercraft	A family of vehicles which ride close to the surface on a cushion of trapped air. They are being utilized for limited passenger and/or freight transportation with a potential for greatly expanded use.	The materials most commonly used in the construction of hovercraft are aluminum and composites. At the present time, these composites are largely glass-fiber-reinforced composites. Later hovercraft will probably utilize improved composite materials such as graphite fiber composites. Hovercraft also have a potential for military utilization.	(This technology is similar to super huge cargo planes in that it utilizes composites which were selected for further study).

Industry	Emerging Technology	Brief Description of Technology	Criticality Consideration(s)	Basis for No In-depth Analysis
Chemicals and Chemical Processes	Fire-Retardant Chemicals	Clothing and cloth are treated with three types of chemicals to give fire-retardant protection: Phosphorous compounds for cotton, bromine compounds for synthetics, and antimony oxide for all types of cloth.	Legislation will probably be passed that will require that all clothing and cloth for wear be treated with fire-retardant chemicals. Large amounts are needed, e.g., 20% of the weight of cotton cloth in chemicals is required - corresponds to 500 million pounds of phosphorous compounds per year. These compounds need elemental phosphorous, for which there is very limited production capacity. Bromine is not in short supply. Antimony oxide imported from Peoples Republic of China and South Africa.	This is a critical area that was not selected for in-depth study on the basis of ranking, i.e., other emerging technologies were judged to have a greater impact on the critical materials situation.
	Use of Titanium Tubing in Highly Corrosive Environments	Titanium tubing is replacing copper-nickel tubing in heat exchanger installations utilizing sea water and in desulfurization systems used in the chemical and petroleum industries. Titanium tubing is also being introduced into the chlorine production process.	Chlorine production now uses 1.5 million pounds of titanium tubing, with an expected growth to 8 million pounds by 1980-1985. Power plants are expected to use 2 million pounds by 1980, and petroleum refineries 1 to 2 million pounds by 1980. The critical problem is production capacity.	Potential problem area, but considered to be less critical than six technologies chosen for in-depth analysis.

Industry	Emerging Technology	Brief Description of Technology	Criticality Consideration(s)	Basis for No In-depth Analysis
Chemicals and Chemical Processes (con't)	New Methods for Increasing the Octane Rating of Gasoline	Because of restrictions on the use of lead in gasoline, other methods are to be used to increase octane rating. Catalytic reforming and alkylation are the major methods. Another candidate is isomerization.	Platinum catalysts are required for catalytic reforming and isomerization. Research is being carried out on new materials for use as catalysts in isomerization.	Market penetration depends on continuation of Environmental Protection Agency regulations. Effect of technology on critical materials judged not as great as that of technologies chosen for further study.
	Hydrodesulfurization of Crude Oil	As the sulfur content of crude oils increase and government limits on sulfur decrease, an increasing amount of hydrodesulfurization is carried out.	Cobalt-molybdenum catalyst impregnated in alumina. A rough estimate is that about two million pounds of cobalt-molybdenum alloy is used in this application per year. Also, possibly titanium tubing.	The rate of growth of this technology is not sufficiently rapid to suggest that a shortage of cobalt-molybdenum catalyst will occur by 1990.
	Recovery of Metals From Heavy Crude Oil	Metals, especially vanadium and nickel, in certain heavy crude oils poison the cobalt-molybdenum catalyst used in hydrodesulfurization. Therefore, attempts may be made to remove these metals prior to hydrodesulfurization, but a viable demetallization process has yet to be developed. Also, U.S. companies exert strong efforts to minimize the amount of high metal heavy crude oils that they import. (Venezuelan crudes and some Iranian crudes, for instance, have relatively high metal contents).	Vanadium and nickel recovered from heavy crude oils may serve as an additional source of supply of these important materials.	Possible source of vanadium and nickel, but the market penetration of the technology by 1990 will probably be low.

Industry	Emerging Technology	Brief Description of Technology	Criticality Consideration(s)	Basis for No In-depth Analysis
Chemicals and Chemical Processes (con't)	Coal Gasification	A variety of processes for producing gas from coal are under investigation. Either high-BTU gas or low-BTU gas is produced, depending on the process.	Alloys and ceramics that are resistant to erosion, wear, and corrosion in complex high-temperature environments and to corrosion in specific liquid environments at lower temperatures. Very thick steel plate, for which U.S. production capacity is relatively small.	Relatively small market penetration projected by 1990.
	Enzyme Production	Enzyme technology is emerging as a replacement for fermentation in the production of agricultural products. Petroleum products, required in fermentation, will not be needed. For example, glucose is being produced from starch.	The production of enzymes is the critical issue and in particular, the substrate upon which the enzymes are grown. Only one company has the technical know-how required to produce the substrate material.	This technology is not directly critical to DoD, but will lower cost of required agricultural products and lower our dependence on foreign supply, e.g., sugar. Important, but criticality not high enough to investigate further.
	Monomolecular Films	Monomolecular films are critical to many processes such as seawater desalinization where a water-impervious layer is required that does not significantly degrade heat transfer. Films now made by a gas plasma process which is difficult to control. Two new processes, photopolymerization and vapor deposition from plasma, are being developed into production processes.	The materials used in these films are not critical.	An important area but one that does not impact on DoD's critical material needs.

Industry	Emerging Technology	Brief Description of Technology	Criticality Consideration(s)	Basis for No In-depth Analysis
Communications	Optical Communications	Optical radiation is coupled into optically perfect waveguides and transmitted over a distance, after which the signal is detected with a high-fidelity sensor.	High-purity low-imperfection glass for use as wave guides not currently available in large quantities.	Availability of high-purity low-imperfection glass may become a problem if the use of optical communications is expanded significantly. However, this materials problem is not as great as in the technologies selected for in-depth study.
	Laser Communications	Laser radiation is transmitted over a distance, either with or without the use of waveguides, after which the signal is detected using a high-fidelity sensor.	High-purity low-imperfection glass for waveguides, if used. Laser materials.	The availability of special glasses for waveguides and of laser materials may be a problem if laser communications grows significantly. (Laser materials and special glasses are being considered further under the emerging technology "Lasers for Materials Processing and Measurement").
	Large-Scale Digital Transmission of Commercial Data	Transmission of commercial data in digital form throughout computer networks.	Materials used are not considered critical.	Negligible usage of critical materials.
	Use of Picturephones for Business Conferences	The use of picturephones for business conferences will eliminate transportation expenses and inconvenience, and save time.	No large quantities of critical materials required in this technology.	No significant effect on critical materials.
	Use of Microprocessors in the Home	Microprocessors (essentially very small computers) can be used, for instance, to translate into digital format periodic changes in the recorded usage of utilities. The microprocessors would yield the desired information when interrogated from a central station.	Critical materials are not involved in this technology.	Small usage of critical materials.

Industry	Emerging Technology	Brief Description of Technology	Criticality Consideration(s)	Basis for No In-depth Analysis
Communications (cont'd)	Computer Monitoring and Control of Processes	The utilization of properly programmed computers to monitor the operating parameters of production processes and to make changes as required.	Materials criticality has not been demonstrated.	Insignificant usage of critical materials.
	Optical Character Readers	This technology involves illuminating planes or volume patterns, such as on a flat surface (e.g., printing) or in a volume such as in a hologram, and processing the detected modulated signal.	No critical materials involved.	No impact on critical materials.
Construction	Fiber-Reinforced Concrete	The use of fibers in concrete is revolutionizing the construction industry. The engineering properties of fiber reinforced concrete are superior to plain or conventionally reinforced concrete and at a lower cost. At the present time, these new materials are being evaluated worldwide.	It is anticipated that, if fiber reinforced concrete is widely accepted, literally millions of tons of fibers will be required. Economic methods for producing fibers is a likely point in this situation.	The fibers used in fiber-reinforced concrete are not critical materials and should not have a significant effect on the DoD materials outlook.
	Pre-engineered Buildings for Home Units	Pre-engineered buildings which were originally represented by "Butler" type commercial buildings will experience a significant jump in the 1975-1990 time period as they enter the home market.	The critical material, if any, is coated metal. Plastic coated steel will probably account for the majority of the materials usage.	The materials involved should not be critical with respect to DoD's needs.

Industry	Emerging Technology	Brief Description of Technology	Criticality Consideration(s)	Basis for No In-depth Analysis
Electronics/ Electrical	Improved Field-Effect Emitters	Research is continuing on oxide-metal composites containing millions of aligned metallic fibers per square centimeter which can produce much higher current densities than normal field-effect emitters.	Production capacity for specific melt-grown oxide-metal composites containing aligned metallic fibers.	Effect on requirements for critical materials by the year 1990 judged to be not as great as that of the six technologies chosen for in-depth study.
	Batteries for Energy Storage and Automobiles	The anticipated demand for peak power through 1990 will have to be supplied by means other than primary power generation. Battery units of 10 megawatt capacity are now planned to meet this need. Several battery types are in development: sodium-sulfur, lithium-sulfur, sodium-chlorine, zinc-chlorine, and, of course, lead. Similar battery types are also under study for automobiles.	Battery types other than lead will not use materials that are in danger of short supply. Our supply of lead has been adequate to date. However, if lead is used, the amount of lead required would be one million tons for peak power by 1990, and six million tons for automobiles by 1985. However, the latter figure is based on a very optimistic projection of 20 million electric cars by 1985.	The amount of lead required for these potential applications could well exceed domestic supply. However, no real problems are envisaged if suppliers have sufficient notice.
	Light-emitting Diodes (LEDs)	Increasing use of LEDs for radiation detection and displays.	Increased demand for current materials (GaAsP, GaP, or GaAs).	Supply expected to keep pace with projected demand through 1990.
	Large-scale Integrated Circuits (LSIs)	The trend is toward finer line widths in integrated circuits. This allows more functions to be performed within a given surface area.	Silicon chips. Organic materials such as polyamides are beginning to replace silicon oxide and silicon nitride as the insulating layers.	No lack of materials or manufacturing capacity is envisioned.
	Infrared Detectors	Increasing use of narrow-band-gap materials for the detection of infrared radiation.	Growing demand for current narrow-band-gap materials (e.g., PbSnTe and HgCdTe).	No serious materials supply problems anticipated through 1990.

Industry	Emerging Technology	Brief Description of Technology	Criticality Consideration(s)	Basis for No In-depth Analysis
Electronics/ Electrical (cont'd)	High-temperature Electronics	Specialty applications may require electronic systems that operate at elevated temperatures in the vicinity of heat sources. These systems would detect, filter, and/or generate radiation. Wide-band-gap materials would be required.	Wide-band-gap materials (e.g., SiC) in the proper purity would be required. Preparation procedures would probably have to be developed for these materials.	Very small market penetration of this technology is projected by 1990.
	Travelling-wave Tubes	Travelling-wave tubes amplify microwaves.	Samarium-cobalt magnets. Possibly mischmetal-cobalt magnets in the future, if compositions are developed with improved properties; these should be cheaper than samarium-cobalt magnets.	Supply and demand expected to remain in-balance through 1990.
	Microwave Generators	As the name implies, this technology involves electronic devices that generate microwaves.	Zone-refined-and-doped single-crystal silicon, or 3-5 compounds (e.g., GaAs and InSb).	No shortage of materials or processing capacity expected by 1990.
	Liquid Crystal Displays	Liquid-crystal-type organic materials can be used as displays, for instance in electronic watches.	None apparent at this time.	No critical materials involved in this technology.
Energy	High-voltage Direct-current Power Transmission	Direct current power transmission at high voltage is advantageous both for long overhead lines and for underground cables. Also, it is beneficial in inter-regional power transfer and can be used to tie systems together asynchronously.	High purity silicon for rectifiers. Additional production capacity may be required.	Projected market penetration by 1990 probably not sufficient to cause serious materials shortage problems.

Industry	Emerging Technology	Brief Description of Technology	Criticality Consideration(s)	Basis for No In-depth Analysis
Energy (cont'd)	Gas Centrifuge Separation Process	Possible replacement for the gaseous diffusion process for uranium enrichment.	Possible use of stainless steel in centrifuges, with a resulting requirement for chromium and nickel.	Large market penetration by 1990 not anticipated.
	Gas Nozzle Separation Process	Replacement candidate for the gaseous diffusion process for enriching uranium.	Minimum requirements for critical materials.	No significant impact on critical materials. Only minor market penetration anticipated by 1990.
	Liquefied Natural Gas (LNG) Operations	Liquefaction of natural gas for long-distance transportation by ships.	9%-nickel steels and aluminum candidates for construction of cryogenic sections of liquefaction plants, LNG tankers, and storage facilities.	Requirements for critical materials judged to be low, and much of the construction could take plàce in foreign countries (presumably using foreign materials).
	Use of Zircalloy Tubing to Clad Nuclear Fuel Elements	Zircalloy (a zirconium alloy) tubing is used as a cladding for fuel elements in nuclear reactors.	Ten million pounds of zircalloy tubing required for new light-water reactor power plants projected to 1990. Possible problem with production capacity for high-purity alloy preparation and tube forming if these plants are actually built. U.S. zircon ore reserves are large, so zirconium itself will probably not be a problem.	Likely that the necessary production capacity will become available as plans for nuclear power plants solidify.
	Direct Conversion of Energy by Magnetohydrodynamics	By moving a column of extremely hot ionized gas (a plasma) through a strong magnetic field at high velocities, magnetohydrodynamics enables direct conversion of heat into electricity. The strong magnetic field is provided by a superconducting magnet.	Columbium (niobium) in superconducting alloys; nickel and chromium in high-strength steels for large magnet supports. Also, production capacity for superconducting alloys. These requirements are for large superconducting magnets for magnetohydrodynamic research; full-scale plants are not expected by 1990.	(The requirements of magnetohydrodynamics for critical materials are considered in Tasks II through IV, under the emerging technology "Superconductors for Power Applications").

Industry	Emerging Technology	Brief Description of Technology	Criticality Consideration(s)	Basis for No In-depth Analysis
Food and Agriculture	Use of Methyl Parathion as an Insecticide	Replacement of DDT, because of its toxic effects, by methyl parathion.	Availability of methyl parathion.	Production capacity readily expandable to meet anticipated needs.
Forest Products	Oxygen/alkali Systems for the Pulping and Bleaching of Wood	Because of environmental problems caused by sulfur-containing emissions in the kraft pulping process, oxygen/alkali pulping and bleaching systems are under development.	No additional requirements for critical materials when switching from a kraft to an oxygen/alkali system.	No added requirements for critical materials.
	Whole-tree Pulping	As the name implies, this technology involves pulping the entire tree -- including limbs, bark and leaves.	Increased consumption of chemicals per ton of product, but these are not critical materials.	No impact on critical materials.
Machinery	Automation	We are on the verge of accelerated expansion in the automation of rapidly moving machinery and mechanisms for production and assembly. The inherent problem of inertia in rapidly moving machinery is forcing designers to utilize lasers in place of mechanical systems for operations such as cutting, drilling sizing and for various measurements. Simple computers will also be used to control the many operations in an automated line.	By 1980 the use of lasers and simple computers will be widespread in the manuracturing area.	Simple computers for these applications will not utilize significant amounts of critical materials. (Materials used in lasers are being considered further in Tasks II through IV, under the emerging technology "Lasers for Materials Processing and Measurement").

Industry	Emerging Technology	Brief Description of Technology	Criticality Consideration(s)	Basis for No In-depth Analysis
Materials	Continuous Casting	The continuous casting of metals is a rapidly expanding technology. Steels and many non-ferrous alloys are now being cast by this method. In the direct casting of copper and aluminum alloys into rod for the electrical industry, the U.S. is now selling considerable equipment abroad.	Sufficient capacity is the potential problem area.	DoD utilizes metals that are continuously cast. However, analysis of the situation indicates that sufficient capacity in continuous casting machines could be built with lead times of only six to eight months.
Medicine and Biomedicine	The Use of Stainless Steel for Blood Catheters	The use of PVC in contact with human blood has been stymied because of toxicity. Accordingly, PVC catheter tubes are to be replaced with stainless steel.	The critical materials are nickel and chromium in the stainless steel. Some one million catheter tubes of PVC will be replaced with stainless steel. This is an increased demand for stainless steel (chromium and nickel). Total amount of stainless would be in the neighborhood of only 30 to 40 tons.	The anticipated demand for additional stainless steel in this application will not significantly affect the supply situation.
	Ceramic Bone Replacements	The use of bioabsorbable ceramics as bone replacements and as tooth roots is a new technology that is just becoming of interest in the U.S. The bone cells invade the porous ceramic and eventually replace it.	The ceramic materials involved are not in short supply and are not considered to be critical.	This new technology does not utilize materials that are critical to the DoD or in short supply in the commercial area.
	The Use of Vitallium and Titanium Alloys as Orthopedic Implants	Stainless steel orthopedic implants are being replaced by vitallium (a cobalt-base alloy) and titanium. These metals are proving to be more resistant to the chemical actions of human tissue and body fluids.	The present demand for orthopedic implants is about 200,000 per year. These have a total weight of about 200,000 pounds.	The materials involved are critical to the DoD; however, the amounts involved are not sufficient to affect the DoD's critical materials situation.

Industry	Emerging Technology	Brief Description of Technology	Criticality Consideration(s)	Basis for No In-depth Analysis
Mining and Minerals Processing	Fused Chloride Electrolysis Process	Electrolysis of fused aluminum chloride which is obtained from alumina by chlorination. This process is a possible replacement for the Hall process, and is said to consume 30% less energy. A 25,000 ton capacity plant is being built in Palestine, Texas, to scale up the process.	Possibility for energy conservation in the production of aluminum.	Critical materials not involved significantly.
Ocean Engineering	Ocean Mining of Manganese Nodules	The recovery of nodules from the ocean floor as a source of nickel, copper, cobalt and manganese is on the borderline of being an economically viable process.	Manganese, nickel, cobalt and copper are all metals imported by the U.S. Manganese and cobalt are almost completely imported, and about 75% of the nickel consumed by the U.S. is imported. The estimated reserve of manganese nodules on the Pacific ocean floor is 1.5 trillion tons, and nodules are forming at the rate of 10 million tons per year.	Although these nodules could supply metals that are important and critical to the DoD, and the potential supply could materially decrease our dependence on foreign sources, it is anticipated that the production of these metals from nodules will not have a significant effect on our supply situation before 1990.
	Offshore Mining	Possible expansion of offshore mining to include other materials in addition to gravel, sand, and phosphate.	Chromium and nickel in high-strength steels.	Market penetration by 1990 probably will be insufficient to impact on critical materials needs.

Industry	Emerging Technology	Brief Description of Technology	Criticality Consideration(s)	Basis for No In-depth Analysis
Transportation	Microcomputers (Microprocessors) for Automobiles	The use of microcomputers in automobiles is rapidly approaching reality. Microcomputers will control functions such as fuel injection, spark plug adjustment and braking to prevent skidding.	When microcomputers come into such use, annual requirements in automobiles and trucks could approach 10 million production units.	An emerging technology but not utilizing significant amounts of materials critical to DoD.
	Levitated Trains	Trains suspended by magnetic forces can attain much higher speeds than can conventional trains. Magnetic forces for the suspension system are supplied by superconducting magnets.	Columbium (niobium) in superconducting alloys. Production capacity for Nb_3Sn and NbTi superconducting alloys.	U.S. market penetration by 1990 judged insufficient to impact on critical materials. (Also, the requirements for superconducting alloys are being considered in the further study of the emerging technology "Superconductors for Power Applications").
Waste Treatment and Environmental Control	Waste-to-Energy Systems	Systems used to convert waste materials into energy, thereby performing the two valuable functions of waste disposal and energy production.	Chromium and nickel in specialty alloys.	Market penetration anticipated by 1990. Should not have significant demand impact vis-a-vis other needs for specialty alloys.
	Recycling of Materials from Refuse	Efforts have been made to recycle ferrous and nonferrous metals, and other materials such as rubber and glass, from refuse.	Possible source of materials, some critical.	Recycling of most materials from refuse is uneconomical at present, except in a few special cases (e.g., when customers bring aluminum beer cans to a central collection point, thus obviating the need for special separation equipment). Probably will not serve as an important source of supply of critical materials by 1990, unless the scarcity of related critical materials increases greatly or materials costs rise significantly.

Industry	Emerging Technology	Brief Description of Technology	Criticality Consideration(s)	Basis for No In-depth Analysis
Waste Treatment and Environmental Control (cont'd)	Desulfurization of flue gases from electric power plants	A number of processes for removing the sulfur from flue gases from electric power plants, and thereby decrease air pollution, have been developed	Chromium and nickel in alloy steels. Titanium tubing	Requirements for critical materials by 1990 judged insufficient for further study

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The report presents a report of an assessment of the materials involved in certain U.S. emerging industrial technologies with the end objective of identifying potential procurement and development problem areas in critical materials for the Department of Defense.

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